IRON AND STEEL

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A TREATISE ON THE SMELTING, REFINING, AND
MECHANICAL PROCESSES OF THE IRON AND
STEEL INDUSTRY, INCLUDING THE CHEMICAL
AND PHYSICAL CHARACTERISTICS OF WROUGHT
IRON, CARBON, HIGH-SPEED AND ALLOY STEELS,
CAST IRON, AND STEEL CASTINGS, AND THE
APPLICATION OF THESE MATERIALS IN MA-
CHINE AND TOOL CONSTRUCTION

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IN COLLABORATION WITH PROMINENT METALLURGISTS
AND STEEL-MAKERS

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PREFACE

As the transformation of crude iron ore into various classes or grades of iron and steel requires the knowledge of the chemist, the experience and skill of the iron- and steel-maker, and a great variety of mechanical and electrical equipment for the various processes, many volumes of this size would be needed to cover every phase of iron and steel manufacture. No attempt, therefore, has been made to prepare a complete treatise for metallurgists and other specialists connected with the manufacture of iron and steel, but rather a text-book suitable for students in technical schools and those in the machine building and mechanical engineering fields who want a broad general survey of the iron and steel industry, with definite practical information pertaining to the various commercial forms and grades of iron and steel products, and the particular class of service for which the different grades are applicable.

Steel having almost any desired physical characteristics may now be obtained and great progress has also been made in the making of iron and steel castings, but these products of the steel-maker and metallurgist have not always been used to advantage by the designer and manufacturer. Expensive materials are often employed where cheaper grades would meet every requirement, or this order may be reversed, low-grade products being used where the best and most costly materials would ultimately prove economical. Because of these facts, the relation between the different grades and qualities of iron and steel and the particular use for which each kind is adapted are emphasized in this book.

The various refining and mechanical processes of the iron and steel industry have been described quite completely in some instances because of the close relationship between the manu-

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facturing method and the characteristics of the product. The chapters dealing with iron ore and the making of pig iron are followed by others on wrought iron, structural steels, tool steels, alloy steels, cast iron, steel castings, and the methods of rolling and drawing bars, flat plates, shafting, and wire. It is believed that the treatment of these different subjects will be appreciated by designers of machinery or tools as well as manufacturers and workers in metal who realize that a knowledge of the materials which are so closely related to their work is of great value if not absolutely essential, especially at the present time when so many different grades of iron and steel may be obtained from the steel mill and foundry.

THE AUTHORS.

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CHAPTER I

CLASSIFICATION OF IRON AND STEEL AND REVIEW OF MANUFACTURING PROCESSES

THE term "iron," as used in the chemical or scientific sense of the word, refers to the chemical element iron or pure iron, which is the chief constituent in all commercial iron and steel. As applied to the commercial product, however, the term "iron" is most generally used to indicate wrought iron, as distinguished from steel or cast iron. Pure iron is not used in the industries, but all the commercial products containing iron as the chief element — wrought iron, cast iron, steel castings, Bessemer steel, open-hearth steel, crucible steel, alloy steel, etc., — contain also small percentages of carbon and a number of other elements, the presence of which determine the characteristics of each class of commercial iron and steel. Iron is found in nature in the form of iron ore, and all the irons and steels used in the industries are produced from iron ore by a number of different processes, each suited to the ultimate product desired.

Pure Iron. — Iron is one of the most abundant elements in nature, and is estimated to constitute by weight 4.3 per cent of the earth's crust. It excels all other metals in magnetic properties, and when small percentages of other elements are added to it, it excels in strength and in the property of attaining great hardness or ductility by suitable heat-treatment. It can also be easily welded and forged. Because of its abundant supply and its strength, ductility, and malleability, iron is the most important of the metallic elements, and present civilization would be impossible without it. Over seventy-five million tons are now used annually for rails, wire, machinery, structural materials, cutting tools, etc.

Pure iron is silvery white, tenacious, malleable, ductile, and has a high melting point. The chemical symbol of iron is Fe, its atomic weight is 55.84, and its specific gravity, 7.84, giving a weight per cubic inch of 0.283 pound. Its linear expansion per unit length in degrees F. is 0.0000065, and its average specific heat for temperatures between 60 and 212 degrees F., 0.11; this value of the specific heat increases with the temperature, up to about 1550 degrees F., and then diminishes. The melting point of pure iron is given by the Bureau of Standards as 1520 degrees C. (2768 degrees F.), but as temperatures above 1000 degrees C. are difficult to measure exactly, it should be understood that the figures given are not known exactly to within more than five or ten degrees. Commercial iron or steel which contains carbon, silicon, phosphorus, sulphur, etc., has a lower melting point, carbon especially having the property of reducing the melting point as well as the ductility of the metal, but increasing the hardness. The amount of the other elements present affects the properties of the iron and steel for different purposes. Variations in the mechanical working and heat-treatment of iron and steel also produce corresponding variations in the properties of the commercial metal. Pure iron is attracted by a magnet, but does not retain magnetization. When exposed to the atmosphere, it is rapidly oxidized or corroded, the corrosion generally being termed " rust."

Commercial Iron and Steel. — As mentioned, all commercial iron or steel contains iron as the chief constituent, but the percentages of carbon and other elements that iron or steel contains and the methods by which they are produced, as well as the processes to which they may be subjected, so change the characteristic properties that there are many distinct forms of iron and steel, some of which have properties so different as to appear like different metals. The main classes are pig iron, wrought iron, Bessemer steel, open-hearth steel, crucible steel, alloy steel, cast iron, and steel castings. Pig iron is the product into which the iron ore is first converted in a blast furnace. From pig iron, all commercial irons and steels are made. Wrought iron is produced by what is known as the " puddling"

process. It contains a lower percentage of carbon than other forms of iron and steel, and is fibrous, ductile, and malleable. When heated, it can be formed and shaped by forging, with great ease, and can readily be welded; hence it is the best known material for making chain, crane hooks, etc. Bessemer steel is made from pig iron in a Bessemer converter; hence its name. Open-hearth steel is produced from pig iron in a so-called "regenerative" furnace, the hearth of which is exposed to the action of the flame. Steel made by both the Bessemer process and the open-hearth process is used for rails, and also for structural iron shapes. It is also often known as "mild steel" or "machine steel." Crucible steel is made from high-grade wrought iron, by adding carbon to it, by melting the wrought iron in crucibles containing the proper amount of powdered charcoal. Crucible steel generally contains a larger percentage of carbon than any of the other steels, and is frequently termed "tool steel," because it is mainly used for cutting tools. Alloy steels may be made by any of the processes mentioned, by adding other metals, such as chromium, nickel, tungsten, etc. Cast iron is generally produced from pig iron in what is known as a "cupola" furnace. It contains a larger proportion of carbon than any of the other forms of iron or steel, and is easily cast in molds, but is neither ductile nor malleable. Steel castings are made from steel, generally melted in an open-hearth furnace, electric furnace, or a small Bessemer converter; crucible steel castings are also made.

At one time, there was quite a distinct line of demarkation between wrought iron and steel, but now these are distinguished mainly by their physical characteristics, wrought iron having a fibrous structure, while steel has more of a grain or crystalline structure.

Classification of Iron and Steel. — At the Brussels Congress of the International Association for Testing Materials, held in September, 1906, the following definitions of the most important forms of iron and steel were adopted:

Alloy Cast Iron. — Iron which owes its properties chiefly to the presence of an element other than carbon.

Alloy Steel. — Steel which owes its properties chiefly to the presence of an element other than carbon.

Basic Pig Iron. — Pig iron containing so little silicon and sulphur that it is suited for easy conversion into steel by the basic open-hearth process (restricted to pig iron containing not more than 1 per cent of silicon).

Bessemer Pig Iron. — Iron which contains so little phosphorus and sulphur that it can be used for conversion into steel by the original or acid Bessemer process (restricted to pig iron containing not more than 0.10 per cent of phosphorus).

Bessemer Steel. — Steel made by the Bessemer process, irrespective of carbon content.

Blister Steel. — Steel made by carburizing wrought iron by heating it in contact with carbonaceous matter. (Also known as "converted steel.")

Cast Iron. — Iron containing so much carbon or its equivalent that it is not malleable at any temperature. The line between cast iron and steel is generally drawn at 2.20 per cent carbon.

Cast Steel. — The same as crucible steel; obsolete, and to be avoided because confusing.

Charcoal Hearth Cast Iron. — Cast iron which has had its silicon and usually its phosphorus removed in the charcoal hearth, but still contains so much carbon as to be distinctly cast iron.

Converted Steel. — The same as blister steel.

Crucible Steel. — Steel made by the crucible process, irrespective of carbon content.

Gray Pig Iron and Gray Cast Iron. — Pig iron and cast iron in the fracture of which the iron itself is nearly, or quite, concealed by graphite, so that the fracture has the gray color of graphite.

Malleable Castings. — Castings made from iron which, when first made, is in the condition of cast iron, and is made malleable by subsequent treatment without fusion.

Malleable Iron. — The same as wrought iron.

Malleable Pig Iron. — An American trade name for the pig iron suitable for converting into malleable castings through the

process of melting, treating when molten, casting in a brittle state, and then making malleable without remelting.

Open-hearth Steel. — Steel made by the open-hearth process, irrespective of carbon content.

Pig Iron. — Cast iron which has been cast into pigs direct from the blast furnace.

Puddled Iron. — Wrought iron made by the puddling process.

Puddled Steel. — Steel made by the puddling process, and necessarily slag-bearing.

Refined Cast Iron. — Cast iron which has had most of its silicon removed in the refinery furnace, but still contains so much carbon as to be distinctly cast iron.

Shear Steel. — Steel, usually in the form of bars, made from blister steel by shearing it into short lengths, piling, and welding these by rolling or hammering them at a welding heat. If this process of shearing, piling, etc., is repeated, the product is called "double shear steel."

Steel. — Metal which is malleable at least in some one range of temperature, and, in addition, is either (*a*) cast into an initially malleable mass; or (*b*) is capable of hardening greatly by sudden cooling; or (*c*) is both so cast and so capable of hardening.

Steel Castings. — Unforged and unrolled castings made of Bessemer, open-hearth, crucible, or any other steel.

Washed Metal. — Cast iron from which most of the silicon and phosphor have been removed by the Bell-Krupp process, without removing much of the carbon, so that it still contains enough carbon to be cast iron.

Weld Iron. — The same as wrought iron; obsolete and needless.

White Pig Iron and White Cast Iron. — Pig iron and cast iron in the fracture of which little or no graphite is visible, so that their fracture is silvery and white.

Wrought Iron. — Slag-bearing malleable iron which does not harden materially when suddenly cooled.

Outline of Iron- and Steel-making Processes. — In outlining the different processes for the production of iron and steel, the method of obtaining pig iron from the iron ore is the basic
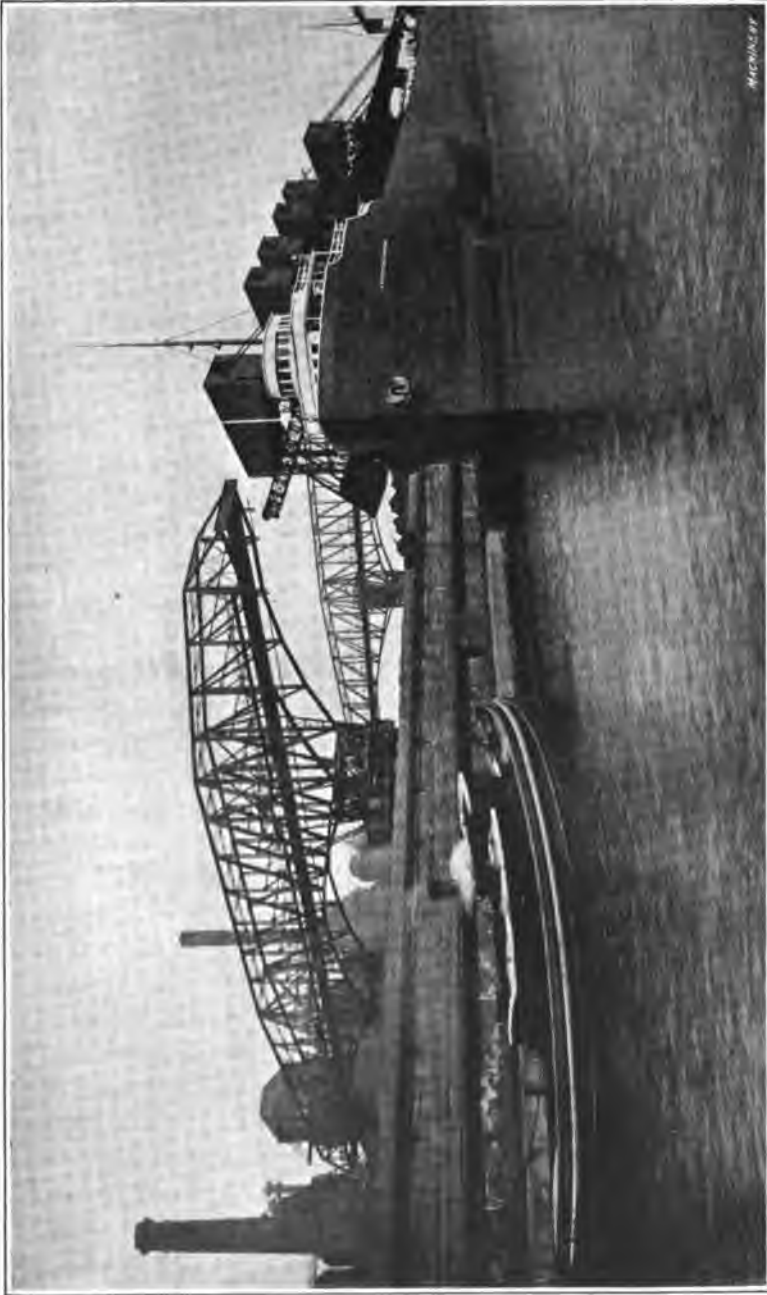
Ore Steamer Unloading Ore at a Blast Furnace

process. When iron ore, which is an oxide of iron containing, ordinarily, from 35 to 70 per cent of pure iron, is placed in a blast furnace, together with limestone, which is used as a flux, and melted with either coke, anthracite coal, or charcoal used as a fuel, the metal obtained is commercially known as "pig iron." The flux serves the purpose of uniting with the impurities of the ore and forms cinder or slag, which is withdrawn from the furnace at intervals. The fuel furnishes the required heat for melting the ore. As the impurities are removed from the ore in the form of slag, metallic iron is formed, which is drawn from the furnace and cast into small bars, known as "pigs," unless it is to be converted into steel by the Bessemer process without being cast into "pigs," which is a modern method. (The accompanying illustration shows an ore steamer, the unloading equipment, and, in the background, a blast furnace.) Pig iron contains about 93 per cent of pure iron, from 3 to 5 per cent of carbon, and some silicon, phosphorus, and sulphur. Pig iron is used in foundries for making iron castings, and in connection with the puddling, Bessemer, and open-hearth processes for the production of wrought iron, Bessemer steel, and open-hearth steel, respectively.

Wrought Iron. — In the making of wrought iron, pig iron is melted in what is known as a "puddling" furnace, in which most of the silicon, carbon, and phosphorus in the pig iron are separated from it, forming puddle cinder. The temperature of the puddling furnace is high enough to melt pig iron, but is not high enough to keep wrought iron in a liquid state, pig iron melting at about 2100 degrees F., while wrought iron melts at about 2700 degrees F. On account of this difference in melting temperatures, small particles of iron, when they have become free from the impurities, will partly congeal, forming a spongy mass in which the iron is in a semi-plastic state. This mass is divided into puddle balls or lumps of about 200 pounds each, which are formed into "blooms" and then, while still hot, rolled into bars. These bars are generally cut up and again heated and rolled one or more times, according to the degree of refinement of the wrought iron required.

Bessemer Steel. — Bessemer steel is made by placing molten pig iron in a large container, known as a "converter," in which the impurities are oxidized and removed by blowing air through the molten mass, from the bottom of the converter, the compressed air having sufficient pressure to prevent the molten metal from entering the holes or tuyeres through which it is blown into the converter. Generally, the carbon in the molten metal is almost entirely burned out, and then a certain amount of spiegeleisen or ferromanganese, containing large percentages of carbon, is added in a liquid form to give the steel the proper amount of carbon and manganese for the purpose for which it is intended. The liquid steel is then poured into ingot molds, and the resulting ingots, while still hot, are rolled into blooms, billets, or rails.

Open-hearth Steel. — Open-hearth steel is made by removing the impurities in the pig iron on the hearth of a regenerative furnace, the hearth being exposed or open to the action of the flame from the fuel. The heat is produced by burning gas from bituminous coal; oil and natural gas may also be used. To the charge of molten metal is added certain proportions of ore, iron scale, or other oxides, the chemical reaction of which keeps the molten iron in a state of agitation. Scrap of wrought iron or steel may also be used, because the high temperature in the furnace will readily melt it. Burnt lime is added to absorb the phosphorus in the pig iron, thus taking it out of the metal.

Crucible Steel. — Crucible or tool steel is made by adding carbon to high-grade wrought iron containing as small a percentage of phosphorus as possible. Small pieces of wrought iron are placed in air-tight crucibles containing the required amount of powdered charcoal. This charge is then melted in a furnace and the metal cast into ingots, which are hammered and rolled to the required size. If the steel is to contain chromium, tungsten, etc., these ingredients are also added in the crucible. The adding of carbon to wrought iron, in order to convert it into tool steel, gives the latter the property of being capable of hardening; that is, of assuming greater hardness if heated to a given temperature and then quenched in water or oil.

Cast Iron. — Cast iron is made from pig iron by melting the pig iron in a cupola furnace and adding certain percentages of cast-iron scrap. Cast iron may be either gray or white, according to the form in which the carbon in it is present. When the carbon is in the "graphitic" form, the fracture is gray in color, and, hence, the iron is known as "gray iron"; when present in the combined form, the fracture is mottled or white, and the product is known as "mottled iron" or "white iron." Cast iron, after having been melted in the cupola furnace, is poured in the molten state into molds shaped according to the required size and form of the castings it is desired to make.

Malleable castings are made from white iron castings by heating the latter to a high temperature in retorts or annealing pots, together with hematite ore. The oxygen in the ore absorbs the carbon in the iron so that the surface of the cast iron assumes the nature of steel, and, hence, is stronger and tougher than is ordinary cast iron.

Steel Castings. — Steel castings are made from metal melted either in an open-hearth furnace, a Bessemer converter, an electric furnace, or in crucibles. The raw materials used for steel castings are pig iron, iron ore, and steel scrap, the bulk of the charge being scrap, so as to give the molten mass the nature of steel. The molten metal is poured into molds the same as is cast iron, but the castings are frequently annealed after having cooled off in the mold. The annealing consists in placing them in furnaces which are heated to temperatures of from 1200 to 1600 degrees F., in which they are kept for a certain length of time, according to their size and the requirements for which the castings are intended. They are then permitted to cool gradually in the furnaces without being exposed to the air.

Brief History of Iron Industry. — Iron is thought to have been used in Egypt, Chaldea, Assyria, and China 4000 years before the Christian era, and to have been known in Middle Europe some time before the invasion of Caesar. Homer speaks of its use by the Greeks twelve centuries before the birth of Christ, and his descriptions show that the working of iron must have reached a high state of development in his time, three

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centuries later. Iron was known in Etruria about as early as
in Greece, and in Gaul, six centuries later, but it was not known
in Ireland and Denmark until the first century of the present
era, and not in Russia and Siberia until eight centuries later.

Iron was first produced in North America along the James
River, Virginia, in 1622, and was made in Lynn, Massachusetts,
nine years later.   Colonel Morris built his "bloomery" in Mon-
mouth Co., New Jersey, fifty years later, and the first forge in
Pennsylvania was built along the Schuylkill, in 1717.   In 1750,
New York's first iron works was built at Stirling, where was
made the 186-ton chain that was used to bar the Hudson river
in 1778. Between 1717 and 1770, the industry had grown
sufficiently for the colonies to export to England about 150,000
tons of pig and bar iron; most of this was exported before 1750.

Because of the ease with which iron is extracted from its ores,
many metallurgists claim that iron must have been known and
worked before copper or bronze, which archæologists say were
the first metals to be used. The metallurgists say that the
absence of iron implements as old as, or older than, existing
copper and bronze ones is due mainly to the rapidity with which
iron is destroyed by corrosion, and the freedom from corrosion
of bronze. Another reason, they say, is that some people con-
sidered iron an impure metal, so that it could not be used in the
burial rites, while the copper and bronze vessels thus used con-
stitute some of our earliest relics. These metallurgists also
say that the use of iron must at least equal, if not antedate, the
use of copper and bronze, because of the greater metallurgical
skill necessary to work the latter successfully, and also because
few places contain both copper and tin ores; but the probability
is that both copper and iron were used in different places at the
same time, and that the use of bronze was developed later.

Analyses of the iron of prehistoric weapons show that many
of the earliest specimens of iron manufacture contain consid-
erable nickel. This particular combination does not occur in
any known ores, but is invariably found in meteoric iron. It is
thought by some that these weapons may have been manu-
factured from meteorites that had fallen to the earth long be-

fore prehistoric man had learned how to dig for and smelt iron in any of the forms of ore found on this planet.

Early Furnaces. — The first iron furnaces were little more than holes in the ground, about two feet square and two feet deep, in which the ore and fuel were placed. The resulting product was a lump of pasty iron that was pulled out of the hole and worked into the desired shape under the hammer. The smith made his own charcoal from the surrounding woods. The method, however, was wasteful of iron, fuel, and labor, and the cast iron and "natural" steel produced by the carburizing action of the fuel were, for a long time, looked upon as undesirable products. Later, the smith learned how to convert these into wrought iron, by remelting them in the fire, and, at the same time, exposing them to the blast in such a way that most of the carbon was burned. Wood and charcoal were the only fuels available, so that the size of the plant was limited. As soon as the trees in the immediate vicinity were burned, it was necessary to haul the fuel a long distance.

The draft required to furnish the heat necessary to melt the metal was obtained by placing the hearth or furnace upon the top of a hill or in a valley, through which strong air-currents frequently passed. Later, the hearths were placed at the small end of wide-mouthed, tapering, covered channels built on the windward side of hills. The blast produced by these natural currents of air, however, was most uncertain, so that artificial means of producing the blast were devised. The first bellows were probably made from the skins of goats. Valves for the bellows were devised about the fourth century.

About the fourteenth century, German metallurgists, seeking to reduce the fuel consumption and the labor cost, increased the size of the forge, especially the height, until it was necessary to drive the blast by water power. The use of this power, in turn, made it possible to increase still farther the size of the furnace. Because of this improvement in iron-making, the iron industry developed so rapidly that, in 1558, an act was passed, in England, forbidding the cutting of wood for iron-making in certain parts of the country. This was done in order that the navy would

not be destroyed by the scarcity of wood for shipbuilding. In 1584, the building of additional iron works in Surrey, Kent, and Sussex was forbidden. By 1756, the scarcity of wood in England became so great that iron was sought in North America; while, in 1750, Parliament prohibited the making of any steel or bar iron in England on the grounds that these works were a common nuisance.

Meanwhile, efforts were made to use coal as a fuel, but the high sulphur content and the opposition of the charcoal makers prevented the adoption of this fuel until 1735. Dud Dudley made both wrought iron and cast iron with coal in 1619, but his methods were never adopted by others. In 1735, Abraham Darby began to use coke as a fuel. Failing in his attempt to use the raw coal, he burnt the coal in heaps on the ground just as wood was burned to make charcoal. The iron made in the charcoal blast furnace was low in silicon and sulphur. As the iron made with the coke blast furnace was higher in sulphur, the temperature of the blast was increased, with the result that the sulphur was eliminated, but a higher silicon content was obtained. At first, it was attempted to reduce the silicon in one operation, and then burn the cinder and complete the refining on the same hearth. This method later developed into the South Wales process, in which the two operations were effected on different parts of the hearth.

In an effort to use coal or coke for the conversion of cast iron into wrought iron, Henry Cort patented the reverberatory furnace, in 1784. In this furnace, the iron lies in a chamber apart from the burning fuel, and is thus protected from the carburizing action of the fuel heated by the flame that the fuel gives out. The first bottoms were made of sand, with the result that the furnace was slow-working, and it was necessary to use an iron low in silicon. Later, air-cooled, cast-iron bottoms were placed beneath the sand-working bottoms. With these furnaces, the iron loss was very great, but it was largely offset by the cheap fuel the furnace made available. Since 1830, however, the pig-boiling process, invented by Joseph Hall, has been the principal method used for producing wrought iron, and is, today,

known by the term "puddling." The reverberatory furnace for puddling has remained unchanged, except for an increase in size and the arrangement of a double furnace which may be worked from each side.

A century ago, when charcoal was used, about five tons were required to produce a ton of pig iron; today, furnaces in Sweden consume considerably less than one ton. With coal it took from eight to ten tons to smelt the ore for one ton of pig iron; today, the coke needed to do the same work can be made from one and one-half ton of coal.

Development of Steel-making. — Prior to the development of the blast furnace, steel was generally produced by heating, in a bed of charcoal, iron bars made directly from the ore, and converting them into steel by deep casehardening. Later, the cementation process was used. This steel, however, was not always uniform in structure and contained a considerable amount of cinder and slag. Benjamin Huntsman, therefore, about 1740, devised the method of melting steel in small covered pots, or crucibles, in which wood or charcoal was placed. By this method, the iron absorbs no impurities from the fire, but absorbs the necessary carbon from the wood or charcoal. The method, however, is too costly, except for steel that must be of the best quality. Most steel is now made by either the Bessemer or the open-hearth processes, and the use of the electric furnace is rapidly growing, especially when a high grade of steel is desired. Since the development of these processes, special attention has been given to the development of steel for special purposes, with the result that steel may now be had that is suitable for nearly any service desired.

Strength of Iron and Steel. — The strength of iron and steel varies considerably according to the quality of the material and the treatment to which it has been subjected. Generally speaking, cast iron may ·be assumed to have a tensile strength of 15,000 pounds per square inch, a compressive strength of 80,000 pounds, and a modulus of elasticity of 12,000,000. Wrought iron may have a tensile strength of from 40,000 to 50,000 pounds per square inch, a compressive strength of from 40,000 to 45,000·

pounds per square inch, and a modulus of elasticity of 27,000,000. Bessemer and open-hearth mild steels have a tensile strength of about 60,000 pounds per square inch, and a compressive strength of practically the same value, with a modulus of elasticity of 29,000,000. This class of steel is that used as structural steel for beams, etc., or as boiler steel for plates. Structural steel for rivets is assumed to have a tensile and compressive strength of about 55,000 pounds per square inch, and boiler steel for rivets, a tensile and compressive strength of about 50,000 pounds per square inch. Spring steel of the best quality may have a tensile and compressive strength of up to 125,000 pounds per square inch. Alloy steels are still stronger, according to their composition and heat-treatment. Steel wire varies in strength according to its condition and quality. Annealed steel wire has a tensile strength of 80,000 pounds per square inch; unannealed steel wire, 120,000 pounds per square inch; crucible wire, 180,000 pounds per square inch; suspension-bridge wire, 200,000 pounds per square inch; plow-steel wire, 270,000 pounds per square inch; and piano wire, 300,000 pounds per square inch. High-class wire is made in fine sizes only, so that these high values for strength per square inch would not apply to a bar actually one inch square, but only when fine wire is drawn from the metal. Annealed iron wire has a tensile strength of about 60,000 pounds per square inch, and unannealed iron wire, 80,000 pounds per square inch. Steel castings are produced in different grades, but may be assumed to have a strength of about 70,000 pounds per square inch, both in tension and compression. These values, of course, are all ultimate strengths, and a reasonable factor of safety must always be adopted, as outlined in text-books on the strength of materials or in handbooks covering this subject.

Varying temperatures have a decided effect upon the strength of iron and steel. Intense cold raises the limit of elasticity of both iron and steel, but does not affect their tensile strength. It reduces their resistance to impact, however. With a rising temperature from that of the normal temperature of 70 degrees F., there is first an increase in strength and then a rapid drop.

If wrought iron is assumed to have a strength of 100 per cent at 70 degrees F., its strength at 400 degrees F. is about 112 per cent and at 570 degrees F., 116 per cent, after which there is a falling off, so that the strength at 750 degrees F. is 96 per cent, and at 1100 degrees F., 42 per cent. Cast iron retains its strength of 100 per cent up to 400 degrees F., but falls from this point to 92 per cent at 750 degrees F. and 42 per cent at 1100 degrees F. Structural steel has a strength of 132 per cent at 400 degrees F., 122 per cent at 570 degrees F., 86 per cent at 750 degrees F., and 28 per cent at 1100 degrees F. Cast steel has its highest value of strength of 125 per cent at 400 degrees F., which is reduced to 121 per cent at 570 degrees F., to 97 per cent at 750 degrees F., and to 57 per cent at 930 degrees F. These figures are, of course, subject to variation, but are given in order to indicate the probable weakening of various irons and steels with increasing temperatures.

CHAPTER II

IRON ORE AND ITS PREPARATION FOR SMELTING

An ore is a material that contains a metal in such quantities that it may be mined and worked commercially for that metal. In an ore, the metal usually is contained in chemical combination with some other element, and, in addition, there are generally various impurities; hence, the condition in which the metal exists in the ore differs greatly. In all commercial iron ores, the metal occurs as an oxide, a carbonate, or a sulphide. The ore may be deposited in beds, lenses, or veins. *Beds* are masses of minerals found in solid stratas; *lenses* or *pods* are irregular masses of ore imbedded in, and separated by, earth or rock; veins fill crevices or seams and generally have quite well-defined walls. Ores having a high metal content are termed "rich"; those having a low metal content are termed "lean."

Commercial iron ore — oxide, carbonate, or sulphide of iron — contains from about 35 to 70 per cent of iron, together with impurities of phosphorus, silica (sand), etc. The highest class of iron ore, when pure, contains 72.4 per cent of iron. When it contains less than 40 per cent of iron, it must first be concentrated, and when it contains less than 25 per cent of iron, it is not considered of any commercial value, because the cost of extracting the iron from the ore is too high to make it possible to sell the product in competition with that extracted from richer ores. The iron ores mined in the United States at the present time contain on an average slightly more than 50 per cent of iron. Those mined in the Lake Superior district, however, sometimes contain over 60 per cent of iron. The best iron ores are those in which the iron is combined with oxygen, forming an oxide ore. Ores which consist of carbonates, that is, minerals in which the iron is present in combination with carbon and oxygen, are also mined, and are of considerable im-

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portance, although they must be roasted to drive off the carbonic acid. The sulphide ores, that is, minerals in which the iron is present in combination with sulphur, are also used, but are of minor importance. These ores must be desulphurized in order to eliminate the sulphur. In fact, all iron ores, whether sulphides or otherwise, which contain sulphur to an amount exceeding one per cent, must be subjected to a special treatment before smelting. The three most important iron ores consisting of iron oxides are *magnetite*, *hematite*, and *limonite*. The carbonate iron ore is known as *siderite* and the sulphide iron ore as *pyrite*.

Magnetite Ore. — Magnetite, the chemical symbol of which is Fe_3O_4, contains, when pure, 72.4 per cent of iron. In this ore, the iron is present as a magnetic oxide, and it owes its name to the fact that it is attracted by the magnet. Magnetite ore deposits are often located by the attraction they assert upon the magnetic needle. In large deposits, magnetite generally occurs in massive crystalline form. It is also found as sand, but metallurgists prefer not to use these sands when it can be avoided. Magnetite is the purest form of iron ore found in nature and contains the largest percentage of iron obtainable in any ore. It has practically the same composition as the black scale formed on iron heated above a red heat, and when pure is almost black. Commercial magnetite ores, however, generally contain some impurities such as sulphur, phosphorus, and titanium, and these ores vary in color through a range of shades from black to blue-black, steel gray, or slightly green. Sometimes the ore is mixed with such a large proportion of rock that the actual percentage of iron for a given weight is comparatively small, and such ore may prove too lean for economical smelting. As a rule, magnetite ore containing titanium has not been used for iron smelting, but of recent years experiments have been made which indicate that magnetite carrying titanium is not necessarily objectionable. As there are very large deposits of these ores in many parts of the world, it is possible that the world's commercial ore supply will, in the future, be increased by these deposits of titanium carrying magnetite ores.

Magnetite has a hardness of from 5 to 6.5 on the Mohs' hardness scale. It produces a black streak on an unglazed porcelain plate. The specific gravity varies from 4.9 to 5.2. As a rule, magnetite ores do not contain any water in combination — that is, they are practically anhydrous, and whatever moisture they contain is driven off by heating them to a temperature of 212 degrees F.

Magnetite ore is found in many parts of the world. There are rich magnetite deposits in the United States in Pennsylvania, New York, and New Jersey, and these supplied the most of the American iron before the discovery of the hematite ore deposits in the Lake Superior region. The ores in the Cornwall ore hills of Pennsylvania also contain copper, which is recovered and through which the cost of the iron obtained from that bed is greatly reduced. Large deposits of magnetite ore are also found in several of the other states. The extensive iron ore deposits in Sweden are largely magnetite, and the well-known Dannemora iron is made from magnetite smelted with charcoal.

Red Hematite Ore. — There are several varieties of hematite ore, but the one generally known by this name is *red hematite*, which is an iron oxide containing, when pure, 70 per cent of iron, and having the chemical symbol Fe_2O_3. The commercial hematites are not pure, however, the richest obtained in the regular mining being those of the Lake Superior district, which contain a maximum of 64 per cent of pure iron and average about 60 per cent. In addition to the hematite ore obtained in the Lake Superior district, this ore is mined in many parts of the United States and in Cuba, Canada, Newfoundland, Spain, Germany, and England. Approximately 93 per cent of the iron ore mined in the United States is hematite ore. The ore is hard or soft, depending upon whether it is found in massive compact rock-like formation or in loose and earthy substances. The color varies from a bluish-gray to a deep red, but the name "red hematite" is due to the fact that the ore always gives a red streak on an unglazed porcelain plate. The hardness on the Mohs' scale varies from 5.5 to 6.5, and the specific gravity, from 4.2 to 5.3. Hematite ore is anhydrous — that is, it con-

tains no water in combination, any moisture contained being driven off by exposing the ore to a temperature of 212 degrees F.

Brown Hematite. — Brown hematite is an iron oxide containing water in combination, and may be converted into red hematite by roasting. When pure, it contains from 60 to 65 per cent of iron, but the commercial hematite ores contain only from 35 to 55 per cent of iron. As a rule, ores of this kind carry a larger percentage of gangue (rocky or sandy non-metallic substances) than red hematite. The brown hematite often contains manganese and usually so much phosphorus that it cannot be used for the Bessemer process, but it seldom contains enough sulphur to cause any trouble on that account. Brown hematite ore is found in beds and veins and often forms the cover of copper ores. It is generally porous and easy to reduce and smelt in a blast furnace. It is often found in clay deposits, and the material mined must then be washed in order to remove the clay and gravel.

Limonite. — Of the brown hematite ores, limonite, the chemical formula of which is $2 Fe_2O_3 + 3 H_2O$, is one of the most important. The color of this ore varies from light brown to black. It gives a yellowish-black streak on an unglazed porcelain plate. The hardness on the Mohs' hardness scale varies from 5 to 5.5, and the specific gravity, from 3.6 to 4. Limonite may be found as "compact," which occurs in various massive forms; "ocherous" or "earthy," which varies from brown to ocher yellow in color and is frequently mixed with clay; "bog iron ore," which is formed in marshy places and is loose and porous in texture; and "brown clay" or "iron-stone," which occurs in compact masses.

Turgite. — Turgite is another ore generally classed as a brown hematite. Its chemical composition is $2 Fe_2O_3 + H_2O$. When pure, it contains 66 per cent of iron. Its color is brown or yellow, with a brown or brownish-yellow streak on an unglazed porcelain plate. The hardness on the Mohs' hardness scale varies from 2.5 to 5.5, and the specific gravity varies from 3 to 4.7.

Goethite. — Goethite is another ore generally grouped as a brown hematite. Its chemical composition is $Fe_2O_3 + H_2O$. When pure, it contains 63 per cent of iron. It has the same appearance, color, and streak as turgite, and has practically the same hardness and specific gravity.

Oolitic Ore. — Oolitic ore is another variety of brown hematite. It occurs in small granules somewhat like fish eggs cemented together with clay, or in siliceous materials, or the grains are foreign matter cemented together by the iron ore. When the gangue is siliceous, this ore is usually of little value; but when the gangue is basic, the ore may be quite valuable, even when low in iron.

Brown hematite ores are found in several parts of the United States, and in Cuba, Spain, Germany, England, and France. Most of the Spanish and Cuban ores are of the brown hematite kind.

Carbonate Iron Ore. — The carbonate iron ore, the chemical symbol of which is $FeCO_3$, is the least desirable of the generally used iron ores. When pure, it contains 48.3 per cent of iron, but the deposits usually include so much barren material that the ore must be washed. This ore is frequently known as "siderite" or "spathic ore." British ores of this kind are frequently also known as "black band," when containing bituminous matter, as in coal seams, and "clay band" or ' clay iron-stone," when found in clay deposits or occurring in shales in conjunction with much clay. This ore must often be roasted before it is charged into the blast furnace, in order to expel the carbon dioxide. The color of the carbonate iron ore varies from a brown or yellow-brown to a gray. Its hardness on the Mohs' hardness scale varies from 3.4 to 4.5, and the specific gravity varies from 3.7 to 3.9. Carbonate iron ores are found, to some extent, in the United States, but are more commonly mined in Great Britain, Germany, Hungary, and Russia. They are of especial importance in England and Scotland, where they form an important factor in the pig-iron industry. Black-band ore produces strong iron and, when mixed with hematite ore, produces a soft, good grade of Scotch iron.

Iron Ores of Minor Importance. — Among the iron ores of minor importance may be mentioned pyrite, ilmenite, and frank-linite. *Pyrite*, the chemical symbol of which is FeS_2, is a sulphide of iron, the pure ore containing 46.7 per cent of the metal. Because of its great sulphur content, this ore cannot be smelted directly, but is first desulphurized, sulphuric acid being extracted from the ore and forming an important part of the product. The residue from the manufacture of the sulphuric acid, known as "blue billy" or "purple ore," is used in the manufacture of low-phosphorus iron. This ore often also contains copper, and after the sulphuric acid has been extracted, this metal is then first obtained by means of the so-called "wet" process, after which the ore finally is used as an iron ore. Pyrite has a yellow color and produces a green or brownish-black streak on an un-glazed porcelain plate. The hardness on the Mohs' hardness scale varies from 6 to 6.5, and the specific gravity, from 4.8 to 5.2. While, at the present time, this ore is of minor importance, it is likely that, when the deposits of the rich oxide ores have been exhausted, it will become of great importance in the iron industry, because there are very large deposits available of sulphide ores.

Ilmenite, or titanic iron ore, is an iron oxide ore containing titanium. Deposits of this ore are found in the United States, in the Adirondack Mountains, and in Canada, New Zealand, Sweden, and Norway. Until recently, these ores have not been considered to be of any commercial importance on account of the furnace troubles usually met with when smelting. Recently, however, ores of this kind have been successfully used.

Franklinite is a magnetite ore containing zinc and manganese. After the zinc has been extracted from the ore, the residue is used for making spiegeleisen, a pig iron containing about 20 per cent of manganese. Only one large deposit of this ore is known; this is located in New Jersey.

Factors Determining the Value of an Iron Ore. — The value of an iron ore depends not only upon the iron content, but upon the impurities and the cost of mining and smelting. Because of the cost of transporting it to the nearest market, lean ore has

been used in the Lake Superior region as ballast for railroads; this same ore would have been considered valuable in other states, where the fuel supply and market are close at hand. In Alabama, ores containing about 38 per cent of iron are used, because the gangue contains so much lime that less flux is required in the furnace; besides, it is mined close to centers of pig iron production and extensive coal fields. An ore may even be too rich to work satisfactorily by itself, as it may not have enough gangue to furnish a sufficient volume of slag; although the usual trouble is to obtain a mixture that is rich enough in iron.

The value of an ore also depends upon the product desired, as an ore that is not at all suitable for one purpose may be entirely satisfactory for another; also, an ore that is not suitable, when used alone, may be very desirable for mixing with another. The value of an ore is also effected by the physical characteristics. The red hematites are most desirable, because they are open and porous, and, therefore, are more easily reduced than the magnetite ores, which, while richer, are denser. The hematites are also less likely to carry objectionable elements, such as sulphur or titanium. Fine ores are undesirable, because they are more difficult to handle and transport, and because they are very likely to cause irregular working in the blast furnace as well as considerable loss from the formation of flue-dust. The amount of moisture in the ore is also an important factor in the determination of the value of the ore, for besides increasing the cost of transportation this water must be driven off in the blast furnace operation, which necessitates greater fuel consumption. The present practice is to market all ores according to their composition, when dried at a temperature of 212 degrees F.

If the chemical composition of an iron ore is known, the approximate proportion of iron that it contains may be determined by multiplying the percentage of the oxide Fe_2O_3 by 0.7; or the percentage of the oxide Fe_3O_4 by 0.72; or the percentage of the carbonate $FeCO_3$ by 0.48. The product thus obtained gives the percentage of metallic iron actually contained in the ore.

Influence of Various Elements on Iron Ore. — The various iron ores when mined are seldom pure oxides, carbonates, or sulphides, but are, on the other hand, generally mixed with mineral matter such as quartz, limestone, and clay containing no iron or other metallic components. These impurities are generally known by the inclusive name "gangue." In addition, a great number of other elements are found in combination with the ore, such as sulphur, phosphorus, manganese, titanium, copper, and nickel, as well as alumina, magnesia, silica, and lime. Of the impurities, sulphur and phosphorus are the most common and, on account of their influence, the most important.

Influence of Sulphur on Iron Ore. — Sulphur is objectionable in an iron ore because it must be removed in the blast furnace by the use of additional flux, provided it occurs in excessive amounts. The use of an additional flux requires an increased fuel consumption and results in a decreased output; hence, it is generally considered advantageous to reduce the amount of sulphur in the ore by roasting it before the ore is fed to the blast furnace. If the sulphur in the ore cannot be readily oxidized, the ore cannot be used for the making of iron or steel, no matter how desirable it otherwise might seem. Sulphur is generally considered objectionable in all classes of iron and steel, if present beyond certain small percentages, and steel specifications usually require a low sulphur content.

Influence of Phosphorus on Iron Ore. — The percentage of phosphorus allowable in an ore before it passes to the blast furnace depends upon the purpose for which the pig iron made from the ore is to be used. For basic steel-making or for foundry purposes, the ore may contain 0.5 per cent of phosphorus to each 100 per cent of iron and still be satisfactory. Phosphorus in moderate amounts is desirable in pig iron intended for cast-iron foundries. Ore of this kind, however, cannot be used if the metal is intended for the making of Bessemer steel. On account of the impossibility of using high-phosphorus ores for the Bessemer process, therefore, iron ores have been divided into two classes, Bessemer and non-Bessemer ores. As Bessemer pig iron must not contain over one part of phosphorus to

1000 parts of iron (0.1 per cent), and as the phosphorus in the fuel and limestone used in the blast furnace also enters the pig iron, the practical limit for the presence of phosphorus in an iron ore that is to be used for making Bessemer steel is limited to 0.07 per cent of phosphorus, or one part of phosphorus to 1400 parts of iron. Non-Bessemer ores do not, as a rule, command as high a price as Bessemer ores, even when they contain the same percentage of iron. Sometimes high-grade Bessemer ores are mixed with non-Bessemer ores in order to produce a mixture which will contain so small a percentage of phosphorus that the mixture may be classed as a Bessemer ore. In ores intended for making open-hearth steel, a higher percentage of phosphorus may be present than in the ores intended for Bessemer steel, but as low a percentage of phosphorus as possible is preferable in either case. Some special low-phosphorus pig iron used in steel-making is made from selected ores and generally commands a higher price.

Richness of Commercial Iron Ore. — The present tendency in the manufacture of iron is to use ores that are less rich than those used in the past, partly because of the scarcity of the richer ores, and also because of the improved methods in mining, transportation, and smelting, which make the leaner ores available. The richness of the iron ore used in various countries is indicated by referring to the amount of ore required to produce one ton of pig iron. In the United States, for example, an average of 1.9 ton of ore is required to produce 1 ton of pig iron; in Sweden and Russia, 2 tons of ore to 1 ton of pig iron; in Great Britain and Germany, 2.4 tons of ore to 1 ton of pig iron; and in France and Belgium, 2.7 tons of ore to 1 ton of pig iron. When native British ores are used alone, as much as 3 tons of ore are required for each ton of pig iron.

Iron Ore Deposits. — The early source of iron ore appears to have been in India, although the Greeks obtained it from the Chalybes, who dwelt on the Southern coast of the Black Sea. The Romans obtained iron ore from Spain and Elba. At present, the United States is the largest producer of iron ore and its ores are much richer than those of most European countries:

however, the nearness of the ore bed to the fuel supply and
the market for the product makes the working of these leaner
ores profitable.   Most of the United States ores are obtained in
the Lake Superior region, yet the yearly production of ore from
mines outside of this region exceeds that of most foreign nations.
Notwithstanding the long distance of the Lake Superior beds
from the fuel supply, the richness of the ores and the efficiency
of the mining and ore-handling methods have enabled this region
to retain its supremacy over the Southern fields, where the iron
and fuel are close at· hand.   In the later fields of the Lake
Superior region, the open-pit method of mining is used, as the
ore lies in beds sometimes 250 feet thick that are from a few feet
to about 100 feet below the surface.   The ore is mined by large
steam shovels and loaded directly into the cars.

The Southern district, which centers around Birmingham,
Alabama, is one of the most advantageous pig-iron making dis-
tricts in the world, as it has the ore, fuel, and flux in a closer
radius than any other; but the ores and fuel are of a compara-
tively low quality.   Much of the ore is concentrated by washing
and all the ores carry a large percentage of silica.

Before the development of the iron deposits of the Lake Supe-
rior region, the principal American ores were the rich magnetites
of New Jersey, New York, and Pennsylvania.   Magnetic con-
centration makes some of this ore the richest produced.   The
United States also imports, in normal times, large quantities of
ore from Cuba, Chile, Spain, Sweden, Canada, Newfoundland,
Africa, and some other countries.   It exports a small amount
to Canada.   The Cuban ore beds are stretched over large areas
and lie at the surface so that they require no stripping.   Com-
pared with the Lake Superior ores, they are of a low grade, but
the cheap transportation and the mining methods available
make the development of these fields very desirable.   The Min-
ette region of Western Germany and Eastern France prior to the
war supplied the ore for the iron industry in those countries as
well as for a part of Belgium.   For the most part, the deposit
is a low-grade oolitic ore, having from 25 to 45 per cent of iron
rather high in phosphorus.   Norway, Sweden, Russia, and

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Finland have large deposits of magnetite. The ore of Norway and Sweden is of high iron content and most of it is very desirable for steel-making. The ores of Russia and Finland contain less iron. Great Britain has large deposits but, like Germany, Belgium, and France, imports large quantities of ore from other nations. Spain, Algeria, Italy, and Greece produce more ore than is used within their boundaries, and China, Chile, Brazil, Mexico, and Venezuela have large undeveloped deposits.

Mining Iron Ore. — The method adopted for mining iron ore depends upon the physical and geological conditions of the deposits, their apparent extent and relation to the surface, the nature of the rocks or earthy materials with which the ore occurs, and the chemical composition of the mineral to be mined. It is also dependent upon the location of the deposit with relation to the market. Large continuous ore deposits covered by a comparatively thin layer of unproductive earth or mineral may be mined by either the open-cut or the underground method. By the *open-cut* method, all the ore is obtained, and expensive systems of supports are unnecessary, but the work cannot be carried on in stormy weather, and large quantities of surface water must constantly be removed. Besides, the mineral mined may be saturated with water and melted snow, and the material removed from the top of the deposit must be disposed of.

The *underground* method has its advantages and is, of course, the only practicable way when a deposit is covered to a considerable depth. By this method, the ore is reached through a vertical or inclined shaft, or through a nearly horizontal passage known as an "adit." Passages, termed "drifts" or "levels," are then driven through the ore or the adjacent rock for the transporting of the ore, which is mined from rooms or "stopes" opening off from these. As the openings are costly and are to be used as long as a deposit is being mined, they must be carefully located. While the shaft or adit is frequently driven in the ore, when possible it should be driven in the adjacent rock so as to be free from disturbance. When driven in the ore, sufficient ore must be left about the opening to prevent its destruction.

As the ore is being mined, holes are drilled in advance of the underground workings to determine the best way in which to work. These holes also show how the ore can be reached to the best advantage when lost through a "fault" or "slip" (displacement or sliding of the ore vein) or "horse" (the infusion of barren or lean metal). They also show whether a vein that is gradually growing thinner "pinches out" (or ends) or at some point farther widens out again, so that it may be profitably worked. When the deposit dips considerably, several levels may be worked at one time, the upper level being farther advanced than the lower. When ore is mined above a given level and allowed to fall, by gravity, through chutes or otherwise, the method is known as "over-hand stoping." When the ore is worked below the given level and is raised, the method is termed "under-hand stoping."

Underground working requires an expensive system of supports, because the place from which the ore is mined must be supported in some manner. Sometimes rock or waste is used for this purpose, but timber is most generally relied upon. This material, however, is unsatisfactory, because of its constantly increasing cost, the frequent renewals necessary, owing to decay, and its liability to catch fire. Concrete, steel, and masonry have, therefore, been used in many places.

Iron Ore Beneficiation. — While some ore may be smelted in the same condition as it is mined, the ore in most cases is crushed, so that the lumps are fairly uniform in size. In addition, iron ore is often treated in some manner in order to remove or eliminate valueless or objectionable components. This treatment is known by the term "beneficiation," which is applied to those processes used for the improvement of iron ore which result in producing an ore containing a greater percentage of the metal to be extracted than the original mined product. Frequently the term is also used to designate those methods which change the physical and sometimes the chemical characteristics of the ore in such a manner that it will be more suitable for the production of any one commercial iron or steel. Seven distinct methods for the beneficiation of iron ore are used, these being:

(1) hand picking or cobbing; (2) washing; (3) jigging; (4) drying; (5) roasting; (6) magnetic concentration; and (7) agglomeration, the latter method being separated into three other distinct methods: briquetting, nodulizing, and sintering.

When beneficiation produces a richer ore, it is evident that more than one ton of raw material is required to produce one ton of the beneficiated ore. For example, an ore containing 40 per cent of iron may be so concentrated that it leaves an ore containing 60 per cent of iron, but it is evident that at least one and one-half ton of the 40-per-cent ore must be used to produce one ton of the richer 60-per-cent ore. In cases when only a change in the physical condition is obtained, the resulting product may be either less or more than the original material, depending upon the process used. Except in the case of agglomeration processes, the complete recovery of the iron content in the ore is seldom secured by beneficiation, because some of the metal is lost in the waste or " tailings." In many cases, it is inadvisable to continue the process of beneficiation to the apparently practical limit, because the cost of the process beyond a certain point is greater than the gain obtained through it.

The term " beneficiation " was formerly applied only to ores of precious metals, such as gold, silver, and platinum, but at the present time it is generally applied to the ores of other metals, including iron ore.

Hand Picking or Cobbing. — The first step in the concentration of an ore is to roughly sort out the worthless material which is mixed with the ore as it comes from the mines, and separate the apparently lean and barren material from the high-grade ore. In the past, this was done altogether by hand, and even now, when the amount of ore handled is small and the labor cost is low, the "cobbing" is performed by men breaking the ore into small pieces and throwing the lean ore and rock into a waste pile. In modern iron mining, however, the ore is broken by crushers and rollers, after which the broken-up material is fed to moving belts which pass before the men who pick out the visibly lean material and throw it away while the balance of the ore is conveyed to bins or storage piles.

Washing. — Washing is another important form of ore concentration. It is employed in order to separate excessive amounts of clay, sand, or gravel from the ore. It is especially applied to red and brown hematite ores which often contain large quantities of such matter. Red hematite, particularly, is often mixed with a large amount of clay, and often from three to four tons of ore must be handled before one ton of commercial ore is obtained. Special devices known as "log-washers" in which a stream of water flowing in an opposite direction to that in which the crushed ore moves are used for separating the clay and lighter material.

Jigging. — The process of jigging is somewhat similar to that of washing, and is used for removing excessive amounts of clay, sand, and rock in ore which is too fine to be successfully treated by the ordinary washing method. In some cases, the fine material from the washers or screens, or both, is also fed to this second washer or jig, where a further separation of ore and waste material takes place, the separation depending upon the fact that the iron ore has a higher specific gravity than most of the gangue or useless material with which it is mixed. In the jigging process, the material is moved in water, or water is forced through it. In this way, the heavier substances form layers on the bottom while the lighter materials come closer to the surface and can be removed. Gates adjusted at various heights permit the ore to be separated from the waste materials. By treating material of only one size in a jig, accurate separation can be made, but it is necessary that the material is of reasonably uniform size in order to obtain good separation.

Drying. — Ores containing an excess of moisture are usually dried. The drying is done for two purposes: It reduces the freight rate proportionately to the iron content, and it produces a richer ore for the blast furnace. For example, an ore containing 45 per cent of iron and 10 per cent of moisture will, when thoroughly dry, contain 50 per cent of iron, by weight.

Roasting. — Roasting is used to remove excessive moisture from damp ores and, especially, to remove combined moisture from hydrated ores, such as brown hematites, which contain

water combined mineralogically with the iron oxide. Roasting
is also employed for driving off the carbonic acid from carbonate
iron ores and to reduce the percentage of sulphur in sulphur-
carrying ores. For hematite ores, roasting is also used to aid
in separating clay, sand, and rock from the ore itself, and in
some cases it is employed to convert non-magnetic iron oxides
into magnetic ore. The ore and fuel are charged in the roasting
kilns, generally in layers, from the top, and the roasted ore is
removed from the bottom and screened. Coal, coke, or gas
may be used as a fuel, gas being the most advantageous, especially
when blast-furnace or a similar gas may be used.

The most essential point in roasting is an abundant supply of
fresh air; heat alone will only partly remove the sulphur. Too
high a temperature, however, may cause the ore to fuse and sinter,
and prevent further removal of the sulphur. High sulphur ores,
waste from sulphuric-acid factories, etc., are usually heated in
"mechanical" furnaces in which motion is imparted to the ore
so as to insure an even treatment throughout the mass.

Most of the kilns in general use are of the Gjers and Grittinger
types. Both of these kilns have riveted steel-plate shelves,
lined with firebrick, and are provided with a cone-shaped bot-
tom for the discharge of the roasted ore. The Gjers kiln varies
from 10 to 12 feet in diameter and from 12 to 30 feet in height.
Some of these kilns are provided with hoods and chimneys for
withdrawing the vapors. The ore is under treatment from two
to ten days, and the furnaces have a fuel consumption of from
50 to 100 pounds per ton of ore. Coke, coke breeze, or anthra-
cite is the fuel used.

When producer or blast-furnace gas is burned, the Davis-
Colby kiln is extensively used. In this furnace, the ore is
dumped into an annular chamber and is roasted by gases enter-
ing from a separate combustion chamber.

Transforming Ore into Magnetic Oxide. — Frequently, when it
is desired to enrich a non-magnetic ore, the ore is roasted until
it reaches the form of hematite, which consists of two parts of
iron and three parts of oxygen. While still hot, the ore is fed
into a second kiln, which is sealed against the entrance of out-

side air and heated in a "reducing atmosphere" (one that can take up oxygen from the ore). This atmosphere is obtained by placing in the kiln, at the same time as the ore, hydrocarbons that have a greater affinity for oxygen than has the ore. This treatment converts the hot ore into "magnetic oxide," which consists of three parts of iron and four parts of oxygen, by removing part of the oxygen.

Magnetic Concentration. — As magnetic ore is richer than non-magnetic ore, magnetic separation is used for separating the strongly magnetic ore from that which is non-magnetic, so as to obtain a richer ore. The process consists chiefly in using magnets for attracting the magnetic ore. By this process, ores too lean to be used directly may be changed into ores that carry from 60 to 65 per cent of iron. Furthermore, impurities of phosphorus and titanium are frequently present in the gangue materials of magnetite, and are either greatly reduced or sometimes almost eliminated. It is also claimed that larger percentages of the sulphur content of magnetic ores containing pyrite or iron sulphide are removed by magnetic concentration than by roasting. A magnetic separating machine must be supplied with only one size of ore at a time, because a magnet that is strong enough to attract large pieces of rich ore will also be strong enough to attract small pieces of a lean ore, and, again, a magnet which is so weak that it can only separate small pieces of good ore from similar pieces of lean ore would not be able to carry heavy pieces of rich ore, and these would then be rejected by the machine at a considerable loss. As a rule, the ore is crushed rather fine before passing through the magnetic separating machines, and the magnetic concentrates are, therefore, too finely divided for furnace use and must afterwards be formed into lumps or briquets by the agglomeration method.

In one plant, where the ore is concentrated by the "dry" magnetic process, the ore passes from the crushers to screens with two-inch holes, the coarse material returning to the crushers while the fine is passed to the magnetic cobbers, which pick out the richer part of the ore. The tailings are crushed to pass through a screen with one-inch holes, and are again passed

through the cobbers. As the tailings from this second separation are again crushed and passed through the cobbers, three products — heads, middlings, and tails — are produced.

In one plant using the "wet" separation method, the ore is reduced to lumps ⅜ inch or less in diameter, and is then carried by water to a battery of mills that thoroughly pulverize it. It is then passed through the magnetic separator, which takes the finely divided magnetites from the water and deposits them in settling tanks in which they are partly dried. The tailings pass off as sludge. Successful magnetic concentration depends upon the continuous operation of the concentration plant, the feeding of but one size of ore to the magnetic separating machine, the arrangement of the plant for rapid and thorough inspection, removing as soon as possible all lean material, passing through the drier only the material that must be dried, and preventing all fine material from passing through the rolls.

Agglomeration. — As fine ores are difficult to handle and cause irregular working of the blast furnace, they are formed into lumps, or small masses, by the various processes included under the heading "agglomeration." In addition to the irregular working of the furnace caused by the fine ore, it is also objectionable because a considerable amount of it is blown out by the air pressure as flue-dust, causing a loss of iron and a tendency to congestion in the flues. The finely divided material may be formed into lumps by briquetting, nodulizing, or sintering.

Briquetting. — Briquetting is one of the earlier methods which consists simply in mixing the ore with some binding material and then molding the mass into the form of bricks, or briquets, of suitable size. The binding material must be of such a character that it will be neutral in the blast furnace. Among the binders used are various clays, water-glass, tar, etc. The bricks are generally, although not always, dried in a suitable kiln. An ideal briquet should withstand the influence of water and heat without disintegrating and should be able to resist pressure, stand severe handling, and have a certain porosity.

Nodulizing. — The nodulizing process consists in transforming fine ore into larger lumps by feeding it into large iron cyl-

inders or rotary kilns, like those used in cement-burning, in which the ore is heated until the fine material congeals into firm and porous lumps or nodules. No binder is used in this process. The rotary kilns used are inclined iron cylinders of from 7 to 10 feet in diameter and from 80 to 120 feet long. They are lined with firebrick and revolved upon rollers at from one to two revolutions per minute. The concentrate or fine ore, sometimes mixed with tar, is charged at the higher end, and, after being sintered, is discharged from the lower end in the form of nodules. These may vary in size from about 3 inches in diameter down to lumps that will pass through a 12-mesh screen. As the fuel is fed at the lower end of the cylinder, the highest temperature of the furnace (from 2350 to 2550 degrees F.) is maintained about 15 feet from the lower end. The fuel may consist of pulverized coal, gas, or tar, but the coal must be dry before it is pulverized, and should contain at least 25 per cent of volatile matter. These kilns have a capacity of about 100 tons per day. They must.be cleaned about every ten days, because of the rings of sintered ore that are formed about 15 feet from the lower end. In some cases, these kilns have reduced the sulphur content of the ore from 1 to 0.03 or 0.05 per cent.

Sintering. — The sintering process is also used for producing lumps from the fine ore by means of heat without a binder, the same as the nodulizing process, but the method of producing the heat is different. In this process, the fine ore is mixed with fine coal or coke breeze and fed upon a movable bed or table at a rate that will give the best results for the ore undergoing treatment. The fuel in the bed is then ignited by a gas flame and burned with a forced draft; by means of the heat thus produced, the fine ore is sintered into a slab, when the draft is discontinued. The slabs are then broken into sizes convenient to handle. The high temperatures also drive off the hygroscopic moisture, sulphur, and combined water.

CHAPTER III

PIG IRON AND ITS PRODUCTION IN THE BLAST FURNACE

PIG iron is the product obtained by smelting iron ore in a blast furnace. A mixture of ore, fuel, and flux is charged into the top of the furnace. A chemical reaction takes place by means of which the ore is reduced, and molten iron collects in, and is drawn from, the bottom of the furnace, after which the metal is cast into bars of convenient size, called "pigs," except when it is to be converted directly into steel. It is thus seen that pig iron is obtained directly from the iron ore; it is the raw material used in the production of all other kinds of iron and steel. Pig iron is remelted in a cupola furnace for making ordinary iron castings, and is converted into wrought iron by the puddling process, and into steel of different kinds by the Bessemer or open-hearth processes. It is also the raw material for crucible steel, except that, in this case, two processes are required; first the making of wrought iron from the pig iron, and then the making of crucible steel from the wrought iron Pig iron contains about 93 per cent of iron and from 3 to 5 per cent of carbon, the remainder being made up of varying percentages of sulphur, phosphorus, silicon, and manganese. The terms "pig" and "pig iron" are derived from the original method in which the bars of this iron are cast in depressions in the sand floor about the blast furnace. A runner or feeder, known as the "sow," is provided, and this, in turn, is connected with the depressions and molds for the pig-iron bars, which are at right angles to it. The runner is filled with metal, and from the runner, the molds for the pig-iron bars are filled. This runner and the numerous smaller molds were supposed to resemble a litter of sucking pigs; hence the name "pig iron." In modern practice, there are various other ways for casting pigs. Those cast in the manner described are known as "sand-cast pig," while those made in metal molds or chills are known as "chill-cast

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pig," and those produced in special casting machines, as "machine-cast pig."

The Blast Furnace. — The modern blast furnace is a development of the furnace that originated in the Rhine provinces in
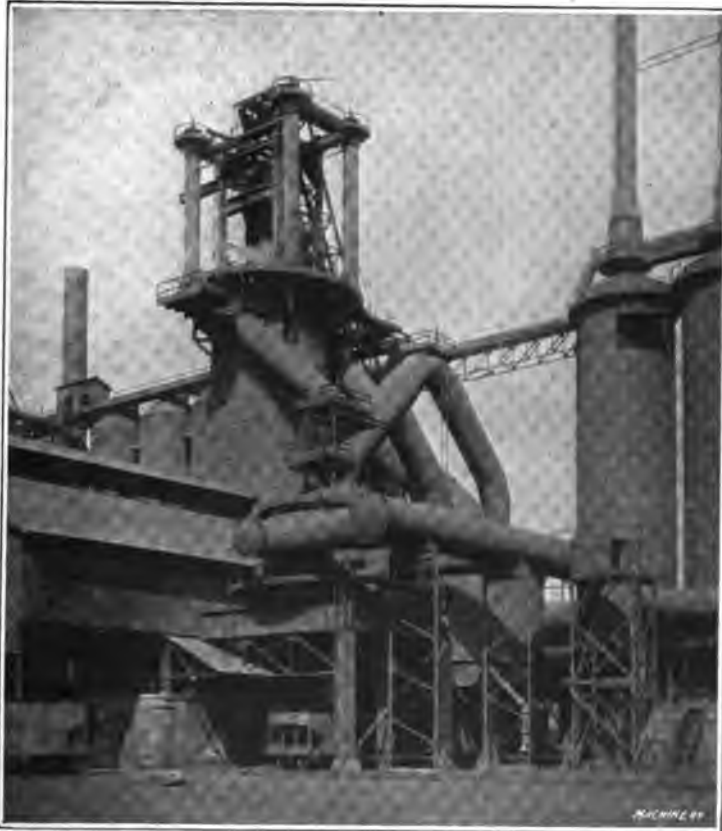
Fig. 1. A Blast Furnace

the early part of the fourteenth century. Aside from experimenting with various fuels and finally adopting coke as the principal fuel, the only changes made in the furnace for about four centuries were in height; as the height was raised, the output and economical working were increased. In 1829, however, J. B. Neilson greatly reduced the fuel consumption and increased the output by warming the blast. In recent years,

James Gayley increased the heat produced in the melting zone, while decreasing the amount of fuel required, by drying the air of the blast.

. While operating on the same principle as the early furnace, the modern blast furnace differs greatly from it. Originally, the furnace was built of solid masonry. Later it was an iron-encased, double brick-wall structure; the outer wall was made of . common brick, and the inner wall of firebrick. The narrow space left between the walls, to allow for contraction and expansion, as well as to prevent the loss of heat through radiation, was filled with ashes. As the loss of heat through radiation has been found to be unobjectionable, and, in fact, lessens the necessity for as frequent repairs, the modern, steel-encased, firebrick, single-wall structure has been evolved. The furnace is, however, only one of the necessary parts of the plant. Its successful operation requires hot-blast stoves and blowing engines for the blast, and other auxiliary equipment. An exterior view of a modern blast furnace is shown in Fig. 1.

Arrangement of a Blast Furnace. — The blast furnace, as shown in Fig. 2 equipped with a mechanical hoist for carrying the charge to the top of the furnace, consists mainly of four parts: The hearth A, the bosh B, the shaft C, and the throat D. The throat and top part of the shaft form the "reduction" or "oxidation" zone; the rest of the shaft forms the "heating" zone; at the junction of the shaft and the bosh is the "melting" zone; between this and the tuyeres (indicated immediately beneath the "B" zone) is the zone of "carburization"; and the lower part of the hearth or the part of the furnace below the tuyeres is the "collecting" zone. Sometimes the bottom of the shaft has parallel sides, but, in most cases, the diameter gradually increases from the throat to the top of the bosh, and then gradually decreases to the top of the hearth, the sides of which are generally parallel, except for a foot or so from the bottom. This constantly increasing diameter of the shaft aids the downward passage of the charge and also provides room for its expansion; while the sloping sides of the bosh support the charge and lessen the pressure on the molten metal in the bottom.

of the hearth. The reduction of this pressure lessens the pressure at the tap hole and permits the metal to be under better control with less liability of cutting the breast as the metal
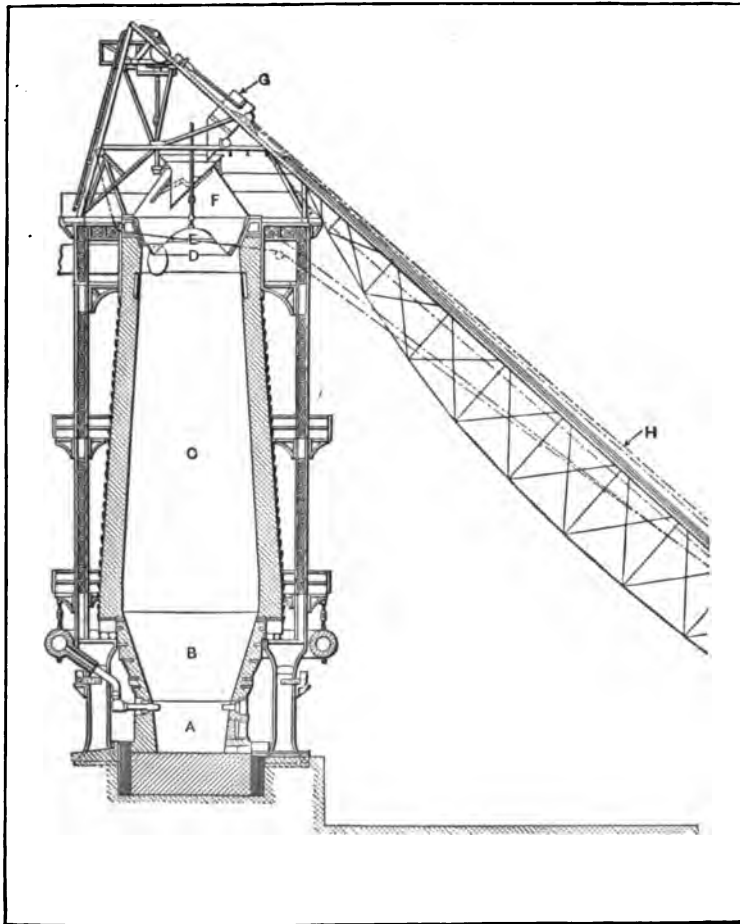

Fig. 2. Sectional View of Blast Furnace

flows out to the runner. This reduction in the diameter of the bosh also makes it easier for the blast to reach the center of the charge.

Size of Blast Furnace and Angles of Walls. — A large furnace is more economical to build and maintain per unit of product

than a small one, but a furnace will not operate satisfactorily if more than 12½ feet wide at the tuyeres. In furnaces of the Pittsburg type, the bosh flares outwards, for 12 feet from the tuyeres, at an angle of from 73 to 76 degrees with the horizontal. The charge will slide easily over the sides at this angle, while a greater angle will cause irregular working. The irregular working is due to the fact that the steeper sides unduly favor the passage of the blast along the walls, instead of up and through the charge, with the result that the outside of the column of the charge is deoxidized more rapidly than the core, which arrives at the bottom in an improper condition. The walls of the shaft make an angle of from 3 to 8 degrees with the vertical. A greater angle leads to irregular working of the furnace. In order that the charge may be evenly distributed, the throat is made rather narrow at the top. If it is made too narrow, the escaping gases will move so rapidly through it as to carry away much of the fine ore; besides, the throttling will give the blowing engines more work to do.

It has been found that 90 feet is the most economical height of furnace, and that the best run is a daily output of 400 tons of iron. This output requires the charging into the furnace of 800 tons of ore, 400 tons of coke, and 100 tons of limestone, each twenty-four hours. During the first four months of 1914, the average daily output of the blast furnaces in the United States was 105,814 tons. The approximate average annual production per furnace, in the United States, is 90,000 tons; in Germany, 50,000 tons; and in England, 35,000 tons. In the United States, about 1 ton of coke is required for each ton of iron produced; in Germany, 1.1 ton is required; and in England, 1.15 ton.

Construction of Blast Furnace. — When a 70-foot furnace with a hearth 9 feet in diameter is completely charged, the base must support 300 tons besides the weight of the furnace. It is, therefore, most essential for the blast furnace to have an especially good foundation. This is often made of firebrick about five feet thick, placed upon a stone or concrete base of about the same thickness, although the exact size varies in each case. The

furnace is a firebrick shell of varying thickness. In the usual construction, the bosh walls are from 18 to 20 inches thick, while the walls of the shaft may be 36 inches thick. The shaft and throat are encased in a steel-plate shell, which, with part of the shaft wall, is built upon an iron ring that is supported by cast-iron columns. A 3- or 4-inch space between the firebrick wall and the steel shell permits of their contraction and expansion. This space is filled with an easily compressible substance, usually slag granulated by being run, while molten, into water. The bosh, however, is not encased by a shell. The brickwork is supported by wrought-iron bands, 6 inches wide and 1 inch thick, placed every two feet in height. The lower part of the hearth is also supported by a thick iron band. Often this part is surrounded by a trough about 8 inches wide and 3½ feet deep, which contains water that is sprayed against the iron plate from a pipe that encircles the hearth. The depth of water in this trough is regulated by valves.

The comparatively thin walls of the bosh are made possible only by the insertion in them of bronze or copper boxes through which water is constantly passing. The boxes are placed in rows that encircle the bosh. These rows are usually located about two feet apart between the tuyeres and the top of the bosh. Sometimes one or two rows are placed below the tuyeres, and two or three above the joint of the bosh and the shaft. When the furnace is to be driven hard, sometimes the bosh is built of cast-iron cooling blocks that have a very thin lining of refractory brickwork; these blocks are kept from melting or burning by causing water to circulate through them.

Furnace Top. — In early furnaces, the top of the furnace was open, but now it is closed by a bell *E*, Fig. 2, in order that the heat of combustion and the gases used for heating the blast may be retained. The bell may be moved vertically to admit the charge into the furnace. Above the bell is a *hopper F* in which the charge is placed before it is dumped into the furnace. In modern equipments, this hopper is charged by *skips G* traveling on a hoist *H*. These skips dump automatically and are usually filled direct from the bins or cars. As the hopper is filled, the

bell is operated by means of steam or blast pressure. Modern furnaces, generally, have a double-bell arrangement so that no gases can escape when the charge enters the furnace, as is the case when the single bell is used. The bell must be hung true, because, if one side should swing lower than the other when the charge is admitted to the furnace, the charge will lodge unevenly, and will have a tendency to cause irregular working. The distribution and position of the coarse and fine material in the charge, and also the formation of irregularities in the mounds that a charge may assume after being dropped by a bell, are dependent upon the angle and diameter of the bell and hopper, compared with the diameter of the furnace at its throat. A comparatively small bell causes the coarse and the fine stock to descend at about the same rate.

Tuyeres. — The complete oxidation of the charge requires that the air necessary be furnished at a pressure of from 6 to 24 pounds. This air is admitted to the furnace through the tuyeres shown at the upper end of hearth A, Fig. 2. The tuyeres are made of a copper alloy that closely resembles bronze, to which it has been found that molten iron has the least tendency to stick. The tuyeres are placed about 6 feet above the bottom of the hearth and project from 6 to 10 inches beyond the furnace lining, in order that the blast may reach the center of the charge and also to protect the lining from the intense heat developed at their ends. To prevent their melting or burning, the tuyeres are placed within bronze boxes through which water circulates; as a rule, the tuyeres may be easily removed from the boxes for repairs or renewal. The tuyeres receive air from a "bustle pipe," which is a steel pipe with a 9-inch lining of firebrick that is placed from 10 to 15 feet above the floor. The bustle pipe and tuyeres are usually connected by a brick-lined "tuyere stock," or "gooseneck," and a blowpipe that fits into the tuyeres. These parts are so connected that they may be easily taken apart for repairs. An opening in the lower end of the tuyere stock permits the tuyeres to be cleaned of obstructions by pushing a bar through it, and a hole, closed with blue glass, in this end, permits the working of the furnace to be watched.

The Blast. — When charcoal iron is being made, a cold blast is used; but when coal or coke is the fuel, a hot blast must be employed. When Neilson discovered the advantages of the hot blast, the temperature of the air was raised by a so-called "hot-blast stove" in stages of 100 degrees F. The experiments showed that much better results were obtained with each 100-degree rise in the temperature until 600 degrees F. was reached, after which there was little improvement until 800 degrees F. was obtained; but, in the rise from 1000 to 1200 degrees F., the results were very much greater than at any other increase of 200 degrees. Many furnace men claim, however, that any increase in the temperature of the blast above 1200 degrees F. is more injurious to the stock than beneficial to the working of the furnace; but temperatures of from 1500 to 1600 degrees F. are sometimes used when the furnace is chilled, and in other emergencies.

As the blast enters the furnace, the oxygen it contains combines with the carbon of the fuel and produces carbon dioxide, CO_2, which is necessary to liquidize the metal and slag. As the gas passes upwards, it combines with more carbon until the reducing agent, carbon monoxide, CO, is formed. The amount of air that must pass through the furnace for the smelting of the ore is much greater than the combined weight of the fuel, ore, and flux of the charge. The amount of heat necessary to decompose this air depends upon the amount of moisture it contains. In summer, the humidity of the air is so great that furnaces do not produce as much iron as in the months when the air is generally drier. Heating the blast does not drive off this moisture; it simply changes it into a vapor that passes into the furnace as steam. It has been estimated that frequently, during the summer months, twenty tons of water are thus transferred into the furnace in one day.

By means of the Gayley process, the moisture is removed from the air by being passed over coils that reduce its temperature to 25 or 30 degrees F., and the moisture is then deposited on the coils in the form of snow or ice. The air, which contains about from 1.5 to 2 grains of moisture per cubic foot, then passes

through the hot-blast stove in the usual manner. The removal of 4 grains of moisture is equivalent to reducing the amount of coke required in the charge about 60 pounds for each ton of pig iron produced. In some cases, the use of this process has reduced the fuel consumption 20 per cent while increasing the output the same amount; besides, the working of the furnace is improved, because the amount of moisture does not vary. The rate of blowing is, perhaps, the factor that affects the output the most; for, as the volume of air is increased, the consumption of the coke and the smelting of the ore are increased. It is,
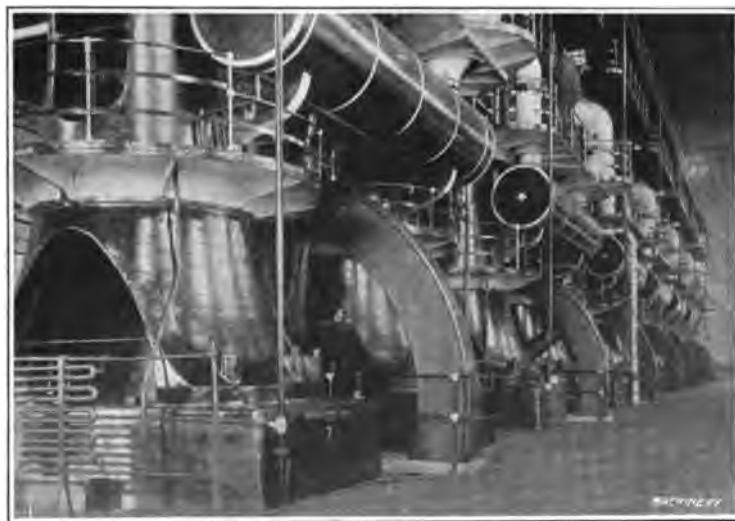
Fig. 3.   Blowing Engines for Blast Furnaces

therefore, important to install good blowing equipment. Fig. 3 shows a view in the blowing engine room of the blast furnace department of the Carnegie Steel Co. (Clairton Works).

Iron Blast Stoves. — When Neilson introduced the warm blast, he passed the air through pipes set in a circular furnace and heated by a coal fire. Later, these pipes were placed upon the top of the furnace and heated by the waste furnace gases; but, when the closed furnace top was adopted, the gases were passed through "stoves" to heat the blast. At first, the stoves consisted of a number of pipes around which the burning gases

passed. Iron stoves, however, are now being displaced by brick stoves, because the iron stoves cannot be economically heated above 900 degrees F., or they will burn out rapidly; besides, fluctuations in temperature cause the pipes to crack, owing to expansion and contraction, while the friction produced by the air passing through the long tortuous passages throws considerable extra work on the engines. Although cheaper to install than the brick stoves, the cost of maintenance is so much greater that (with the reduced cost of smelting, because of the higher temperature obtained with the brick stove) in one case a change from the iron to the brick stove reduced the cost of producing pig iron 30 cents a ton. If the furnace "goes out of blast," for any reason, a wood or coal fire must be built in the iron stove, otherwise the stove may become so cold that, when the gas again enters, it will not ignite but, instead of burning quietly, may explode. Not only must the stove be hot when the gas enters it, but there should be a flame to insure the ignition of the gas. Some furnace men throw a lump of coal or a piece of dry wood into the stove whenever the furnace is shut down.

Brick Blast Stoves. — In the three-pass, center-combustion, regenerative, brick blast stove, the gas from the blast furnace enters at the bottom and immediately ignites, as the air necessary for its combustion is admitted at the same time. The burning gas then passes up a large center chamber until it is deflected by the dome into the narrow flues surrounding this central space; then, passing through large flues at the bottom, it goes up flues along the outside walls and enters the chimney. After the brickwork is heated to the incandescent state, the gas is shut off and the cold blast from the main is admitted into the lower part of the chimney. Passing downwards, the air is deflected by the dome into the outside flues, whence it passes through the small flues and the large central flue into the hot-blast pipe. As soon as the passage of the cold air has cooled the brickwork so that it will not raise the blast to the desired temperature, the cold air is shut off and the furnace gas admitted once more. As a rule, the furnace is "on gas" for about three hours and "on wind" about one.

As the work of the stove is intermittent, three or four stoves are usually provided for each furnace. In a plant of two furnaces, seven stoves are sometimes built, the middle one being arranged so that it can be used by either furnace. Three stoves are generally on gas, while one is on wind. The stoves must be cleaned often of the caked flue-dust, which rapidly collects in the combustion chamber for a height of about 20 feet. As a rule, the stoves are built as closely together as possible and are connected by pipes and separate valves, so that the cold blast coming from the blowing "tubs," and the hot blast leading from the four stoves, come from, and lead into, one main pipe. The "downcomer" — that is, the duct for the blast furnace gas — and the pipes carrying the hot blast to the furnace are either coated with asbestos or are brick-lined, to protect them and prevent loss of heat through radiation. Brick blast stoves are usually about 100 feet high and 20 feet in diameter. When the air and gas pass through the stove only once, the stove is termed a "single-pass" stove; in a "three-pass" stove, the air and gas are caused to pass through three times.

Charging the Furnace. — In early furnaces, the furnace was charged by dumping into it the proper amount of fuel, flux, and ore from hand barrows. To facilitate this work, the furnace was often placed alongside a bank so that the top could easily be reached by means of platforms. As the height of the furnace increased, the barrows were raised to the top of the furnace by elevators. This method made necessary the employment of two gangs of men; one on the ground, loading the barrows and wheeling them to the elevators, and the other at the top taking the loaded barrows from the elevators and dumping them into the furnace. The increased size and output of blast furnaces later required mechanical charging methods to be adopted.

In most modern plants, the charge is placed on skips that are drawn up inclined planes (sometimes perpendicular shafts are used) and automatically dumped. By this method, no men are required at the furnace top, except when necessary to oil or repair the machinery. In the larger plants, two skips are used, running on parallel tracks; one skip goes up with a load

as the other is coming down. It is necessary that the charge be evenly distributed in the furnace. When the hand barrows were emptied into the furnace, the stock was so dumped that each kind of material occupied a different horizontal position in each succeeding charge, or, in other words, the position of each was rotated in successive layers. When mechanical charging was first used, the coarse and fine material separated, with the result that each was dumped on opposite sides of the furnace. The furnace then worked hotter on the side containing the coarse material than on the other, which caused a rapid erosion of the lining on that side; while the fine material on the opposite side of the stack caused an uneven descent of the charge and irregular working of the furnace. While several plans have been tried for the elimination of these troubles, one of the most common devices is a modification of the double bell.

The relative proportions of the charge vary with the nature of the ore, the fuel, and the pig iron to be produced. When red hematite is used, the production of one ton of pig iron requires the charge to consist of 2 tons of ore, 1 ton of fuel, and 0.4 ton of flux; while the use of "clay iron-stone" requires the charge to consist of 2.4 tons of ore, 1 ton of fuel, and 0.6 ton of flux.

Action of Furnace. — As the charge descends, it is penetrated by the gases and chemical reaction takes place. The first material to be affected is the ore, which the carbon monoxide reduces to a finely divided sponge of metallic iron or to a mixture of iron and oxides. In the case of easily reduced ores, this action begins at a temperature of 400 degrees F., but it becomes more rapid as the temperature increases, until 1200 degrees F. is reached, when the action is completed. Some furnace men believe that the action is finished at a temperature of 1000 degrees F. The decomposition of the flux is the second action to take place. Limestone is decomposed into calcium oxide and carbon dioxide, and dolomite is decomposed into magnesia and carbon dioxide. This decomposition is generally thought to take place in the second 30 feet of the descent when the tem-

perature reaches from 1100 to 1600 degrees F. While lime is infusible at the highest temperature of the blast furnace, the silica and alumina of the ore and the ash of the fuel make the lime fusible at the temperature of the hearth, so that it forms the slag.

The fuel is not chemically affected to any extent until it reaches the tuyeres. The only action that takes place is that its temperature is gradually raised, the moisture is expelled, and a little of its carbon is transformed into carbon dioxide. At the tuyeres, however, the blast converts much of the carbon into carbon dioxide, which the excess coke at once reduces to carbon monoxide. Some of the coke is carried into the hearth where it carburizes the metal. As the descending charge reaches the tuyeres, it is melted; the molten iron gathers at the bottom of the hearth, and the slag, being lighter, floats upon it. As the amount of molten matter increases, the slag is drawn off through the slag hole, and the molten iron, which collects at the bottom of the hearth, is tapped at regular intervals. As the charge settles and melts, more fuel, flux, and ore are thrown in at the top in the order named.

After the blast furnace is lighted, it is kept in operation until it needs repairs; sometimes this period of operation lasts a year.

Making the Pigs. — When enough molten iron has accumulated in the furnace, it is drawn out and, when intended for pig iron, allowed to run into molds in which it is formed into pigs; or it is carried by ladles to the mixer (see Fig. 4), from which it is taken to the Bessemer converter or the open-hearth furnace, when it is to be made into steel. The older method of making pig iron is to run the molten metal into sand molds. These molds are formed by making a bed two or three feet deep of the medium grade of bank sand, the bed being made to slope about 18 inches in 100 feet, so that the molten metal will flow easily over it. The metal leaving the furnace passes through the main runner into smaller runners, termed "sows," from which the metal flows directly into the "pigs." These are generally semi-cylindrical in shape, and are about 5 inches wide by 36 inches long, and weigh about 100 pounds. There are usually

about 100 pigs to a sow. After the pigs and sows have solidified enough so that they will not "bleed," they are covered with about $\frac{1}{4}$ inch of sand. Then men wearing shoes with thick wooden soles break the pigs from the sows by inserting, at the point where they are joined, pointed $1\frac{1}{4}$-inch bars. The sows are broken into pieces by prying them up from the molds, or by sledges. As soon as they are broken, a stream of water is turned upon the iron to cool it quickly, so that it may be re-

Fig. 4. Ladle receiving Molten Metal from Blast Furnace

moved and the bed prepared for the next run of iron. Usually two beds are used, one being made ready to receive the molten iron as the iron in the other bed is being removed. In some plants, the pigs and sows are broken by being picked up by a crane and carried to a pig breaker. Here the pigs are broken from the sows and then broken into pieces in order that they may be graded and handled more easily.

Pig-casting Machines. — To reduce the labor cost and also to avoid the work of breaking the hot metal, several methods of

using iron molds have been tried. One of the most widely adopted is by means of a pig-casting machine which consists of a series of iron molds carried by an endless chain. As these molds pass a ladle, they are filled with the molten metal, the speed of the conveyor being properly adjusted for this purpose. One edge of each mold overlaps the mold next to it, so that no metal is spilled. After passing through the air for a short distance, the molds are slowly passed through a tank of water, or, in some cases, up an inclined plane where they are sprayed. They are then dumped into cars and are ready for shipment. As the empty molds return to the pouring end, they pass over a lime vat and are sprayed with a milk-of-lime wash, which preserves them and prevents the pigs sticking to them. This method eliminates the work of making the molding beds, the breaking of the hot pigs, and all handling necessary to ship the iron; besides, the molds chill the pigs, making a harder iron that holds more of the carbon in the combined state. As the iron is free from sand, less time and fuel are required to melt it in the foundry; less flux, too, is required, so that there is less slag to take care of, and a cleaner iron is poured. The pig is more uniform in composition because the iron is tapped from the furnace into a large ladle in which it becomes mixed into a homogeneous liquid, while the pigs from the sand molds are cast just as the iron runs from the furnace, and there is always a difference between the first and the last part of the tap.

The Slag. — The amount of slag formed depends upon the raw materials. With Lake Superior ores, about one-half ton of slag is made for every ton of pig iron produced. As the slag, however, has only one-third the specific gravity of the molten iron, its volume is $1\frac{1}{2}$ times that of the iron. With siliceous mixtures, the weight of the slag may equal, or even exceed, that of the iron produced, so that at least two taps of slag are made for every tap of iron. Less slag is formed in the smelting when charcoal is used than when coke is used as fuel. When tapped, the slag is sometimes run into ladles, in which it is carried to the dump where it is poured in a molten condition. In other cases, it is run from the furnace into long furrows in the ground

from which it is later removed and taken to the dump. Some of the more modern plants run the slag into pits, in some cases 20 feet square and 20 feet deep, and granulate it by allowing a stream of water to strike it when leaving the trough at the mouth of the pit. The granulated slag is later removed from the pit by steam shovels.

Composition of Slag. — The composition of a slag depends upon the grade of iron to be made and the raw material available. As the composition of the slag shows the condition of the furnace and the character of the iron being produced, one or more samples are taken from each tap and placed in iron molds. When the furnace is in a normal condition, the fracture of the chilled sample will be gray in the center and dark toward the outside. If the slag is basic, or "limey," the furnace is hot; the fracture of a sample of this slag will be gray or white in the interior. If the slag is acid, or siliceous, the fractured sample will be black or glassy and thin pieces will be translucent and, in some cases, transparent. The iron produced with this slag will be very low in silicon and high in sulphur; the slag will also contain considerable iron. A cold furnace gives a dull, brownish slag that chills quickly. High manganese or manganiferous ores generally produce a green slag when the furnace is working well, and a brown slag when it is not.

The quality of an iron is largely dependent upon the fusibility of its slag. A refractory slag produces a hot iron, because, as it is slowly fused, it becomes superheated by long contact with the hot gases. A high hearth temperature reduces the amount of sulphur in the iron and increases the amount of silicon, because the hot slag has a greater affinity for the sulphur than the iron, and more silicon is reduced from its oxide and is absorbed by the iron. The slag will not, however, take up more than from 2 to 4.5 per cent of calcium sulphide, in any case.

The fusibility of a slag is dependent largely upon its composition, the more basic being the more fusible. Ordinarily, two-thirds of the manganese in the charge go into the iron, and the other third enters the slag; a hot basic slag causes the manganese to go into the iron. An acid slag, however, attracts more

of the manganese to itself. In the manufacture of ferromanganese, dolomite is used as part of the flux, as the magnesia tends to reduce the loss of manganese in the slag.

Commercial Uses of Slag. — Slag has been used for many purposes in an effort to utilize the immense amount of waste product that is constantly being produced. Among the most satisfactory uses are its employment as part of the aggregate in concrete, and its manufacture into *mineral wool*. The latter is used as a nonconductor of heat, and is packed between the walls and floor spaces of fireproof buildings, etc. One method of making mineral wool is to melt the slag in a cupola and then blow the molten stream into a long, narrow building by jets of water. This is effected by having three flat streams of water strike the molten slag as it issues from the slag hole. Variations in the character of the slag cause different grades of the wool, which is sorted and packed according to its commercial value. There are also differences in the density of the wool at every cast; the lightest is blown the farthest from the cupola and the heaviest is deposited nearest to it.

Fuels for Blast Furnaces. — The fuel used in the blast furnace for supplying the heat must be hard and strong enough to support the charge above it without crushing; if crushed to a powder, it will not properly support the charge of limestone and iron that is placed above it. It must be regular in composition, free from impurities, and in pieces of a good size in order that the heat may pass through the interstices and properly melt the ore. At first, charcoal was used entirely and is still preferred when an especially pure iron is desired. Anthracite and bituminous coal have also been used, but coke is now considered the best for all general purposes, and is the cheapest. Sometimes anthracite and coke are mixed, where anthracite is easily obtained, but generally coke is used alone. For remelting iron, coke is preferred, aside from its cheapness, because it requires less blast and melts the iron more quickly than coal, although coal has some advantages for this purpose. While there is no noticeable difference in the iron made with coke and anthracite, an iron made with charcoal as a fuel is much better

than an iron made with coke as a fuel. Not only is the charcoal iron much lower in sulphur, but there is some additional quality that enables the foundryman to secure better results with it on certain classes of work.

Charcoal. — Charcoal is the charred product of wood and was originally made in mounds, or heaps, from which nearly all air was excluded. It is very porous, light, and retains the wood structure, but will not withstand considerable crushing pressure. It is free from sulphur, but contains a small amount of phosphorus, considerable moisture and volatile matter, and from one-half to three per cent of ash. As a rule, charcoal is now made in retorts, and the waste gases pass to the by-product plant for the recovery of wood alcohol, tar, acetic acid, creosote, etc.

Anthracite. — Anthracite has about the same percentage of sulphur, phosphorus, and ash as coke. Its lack of porosity prevents the free passage of the gases, and thus prevents the rapid and regular burning of the fuel, and causes a strong resistance to the blast. Besides, the coal tends to disintegrate into dust or layers which are apt to pack and clog the furnace and produce serious furnace troubles. At present, bituminous coal is used to a very limited extent; it can be used only in special moderate-sized furnaces.

Coke. — Coke is the product obtained by expelling the volatile matter from certain bituminous coals. It is a strong smokeless fuel composed of almost pure carbon, and is contaminated only by the mineral impurities that exist in the coal. It should be hard, strong, porous, pure, and regular in composition. As a rule, it should have a silvery-metallic luster, and the cells should be well connected and of uniform structure. It is very light and brittle, and depreciates rapidly in shipping. In 1916, the production of the 7500 coke ovens in the United States was over 13,000,000 tons annually.

As it is carbon that furnishes the heat, coke must contain from 80 to 90 per cent of this element. While some of the carbon in the coal is lost in coking, if the process is properly carried on, the percentage lost is not large. The ash generally ranges from 9 to 14 per cent. The less ash coke contains, the

greater is its value, as a rule, although very low ash is not desirable in all cases, because the ash is often beneficial in assisting the formation of a good slag.   Coke should have the least possible sulphur content; however, 1 per cent is not always objectionable.   Sometimes an excessive amount enters the iron, although much of it passes off in the slag.   The amount of sulphur present may be roughly told by dropping pieces of red-hot coke into water, which drives off the sulphur; a comparison of these pieces with the untested coke will show approximately the amount of sulphur the coke contains.   The presence of over 0.9 per cent of sulphur is often shown by the odor of the escaping gases, while a high sulphur content is often shown by yellow spots or stains on the surface of the coke.   Quenching the coke with impure water may increase the sulphur content.

The amount of phosphorus a coke may carry depends upon various conditions; whatever phosphorus a coke contains is generally taken up by the iron being made or remelted.   When the iron is to be used in the acid-Bessemer process, the phosphorus in the coke should not exceed from 0.017 to 0.02 per cent; but for iron to be used in the open-hearth process, the phosphorus in the coke can be much higher, because some of the phosphorus in the iron can be removed in the steel-making process.   Good fresh coke should not possess much over 1 per cent of moisture when protected from rain and snow.   As it takes about 15 pounds of coke in a cupola to evaporate one pound of water, the less moisture a coke contains, the less fuel will be required when melting.   Some claim that exposing coke to the weather reduces the sulphur content, but this fact has never been proved.

At first, coke was made like charcoal in large mounds or piles, but this method was wasteful of coal and did not produce the best results; besides, the time required and the quality of the coke were affected by the weather.   Most of the coke in the United States is now made in a "beehive" oven.   These ovens are built of firebrick and average 12 feet in diameter and 8 feet in height.   They are usually built in a double row, the space between the ovens being filled with clay or loam.   Pillars are

placed between the ovens to support the tracks upon which are run the cars, or larries, for charging the ovens. When the ovens are to be put "in blast," they are brought to the proper temperature by a wood and coal fire, but the coking operation is carried on entirely by the heat retained by the oven walls and that given off by the coal. This heat is retained by the oven from one charge to another, so that no additional heat need be supplied at any time. The air necessary to support combustion is admitted at, or over, the surface, instead of passing through the coal; this prevents the destruction of the coal while burning, and changes it to coke. The coking operation is governed entirely by the amount of air allowed to enter by regulating the size of this opening.

Coking Process. — The action of coking is one of distillation rather than combustion. The heated oven starts the distillation of gas, which ignites when mixed with the air coming through the opening at the top of the door. The combustion of this gas heats the dome of the oven, and in about an hour the coal is ignited. As soon as this stage is reached, a sharp draft is admitted to the oven. After ten or twelve hours, a bright flame covers the entire surface of the coal, which has attained almost a white heat, and passes through the opening in the top. When the bright flame dies out, the coke is simply a red-hot mass containing not much more than 1 per cent of the volatile matter originally in the coal, the greater part having passed off during the time in which the coal was raised to its highest temperature. When all the gas is burnt off, the door is removed and water is poured upon the glowing coke to quench it. In the coking operation, the coal swells approximately one-third in volume for Connellsville coal, and varying amounts for others; after watering, the bulk is a little less than the whole charge. The coke is then drawn, usually by men armed with long-handled scrapers, who let the coal fall upon the platform at the door of the oven. It is later loaded into cars for shipment. The care exercised and the time taken in drawing the coke from the oven has much to do with its size, freedom from "braise," or small coke, and the yield. In large plants, and especially when labor is scarce, the

coke is drawn by mechanical devices which load it directly into the cars; this method, however, breaks the coke much more than the hand drawing. At one time, the coke was drawn and then quenched, but the present method is not only less laborious, but the coke is practically free from moisture, and retains the characteristic silver-gray luster.

Varieties of Beehive Oven Coke. — Beehive ovens are generally operated to produce 48- and 72-hour coke, but 96-hour coke is made in special cases. There is practically no difference in the cokes, as a little more coal is charged for the longer periods to continue the coking process. The usual practice is to charge about five tons of coal, in the ordinary 12-foot oven, during the first four days of the week, and six tons on Friday and Saturday; this plan makes it unnecessary to draw the ovens on Sunday. "Black butts" are the uncoked ends of coal that lay on the bottom of the oven. "Black tops" are caused by the crown of an oven becoming so hot as to fuse the top surface of the coal and thus prevent the free escape of the gases; these will, therefore, deposit lampblack in the cells of the coke that is being formed. "Stock coke" is the name given coke that has been stored in piles at the coke works. Because of the additional handling it receives, this coke is in much smaller lumps than the other. It also contains more moisture and dirt, as it is exposed to rain, snow, dust, and smoke.

Advantages of the Beehive Ovens. — The beehive oven has the advantage of low initial cost, simplicity of operation, and the production of the best possible coke. It also has a low cost of maintenance, because it can be operated by unskilled labor, besides, operations can be discontinued and resumed with less inconvenience and expense than with the retort oven. In order to lessen the waste, some plants now use the gases from the ovens for the generation of steam in boilers, thus using both the combustible part and the heat the gases contain. In such a case, all the ovens are connected by a large flue for the passage of the gases.

Coking Coals. — For coking, coal should be as free as possible of sulphur, phosphorus, and ash. Some of the sulphur is

driven off in the coking operation, but the phosphorus and ash remain unchanged. As a result, the coke has a higher percentage of these properties than the coal, because it requires practically $1\frac{1}{2}$ ton of coal to make one ton of coke. In order to increase the coals available for coking, coal that contains considerable slate or iron pyrites is used after it has been cleaned. This cleaning may be done by the wet or the dry method, the former being preferred. In either case, the aim is to remove the greatest amount of impurities with the least amount of coal passing off with the dirt.

The "dry" method is the cheaper, as it consists only of the crushing and screening of the coal. This crushing is so effected that the coal is broken small enough to pass through screens, while the impurities, which are harder, are too large. In the "wet" method, the coal is separated from the heavier impurities by "jigs." The coal, which is first crushed, is carried by water to tubs in which it is constantly agitated, so that the heavier substances settle at the bottom, while the coal floats off. The washing process, however, often removes so much bituminous coal with the slate as to rob the coal of most of its coking qualities. Coke made from washed coal contains less ash and sulphur than that made from unwashed coal.

By-product Coke Ovens. — Retort ovens were first used for coking coals that could not be satisfactorily coked in the beehive oven. In its simplest form, the retort oven is a firebrick chamber surrounded by heating flues and provided with a pipe through which the products of distillation may be carried off. After the chamber is filled with coal and sealed, the heat in the surrounding flues breaks up the coal and drives off the volatile matter, leaving the coke behind. This volatile matter passes through apparatus which separates the tar and ammonia from the gas. About one-half the gas is used for heating the oven, and the rest is valuable for power, illumination, or for other purposes. In many cases, these ovens complete the coking process in twenty-four hours. In the best American practice, this time has been reduced to eighteen hours. Good coke has been made in less time than this, but the high temperature neces-

sary causes a rapid deterioration of the oven; besides, as the time is reduced, the amount of tar and ammonia obtained is lessened.

Among the principal types of ovens in the United States are the Semet-Solvay, Koppers, Otto, and Coppee. The ovens in most common use are modifications of the Coppee vertical-flue oven and the Simon-Carvès horizontal-flue oven. In any case, however, an installation consists of a number of simple ovens built side by side to form a battery. In general, the ovens are from 35 to 40 feet long, 10 feet high, and from 17 to 22 inches wide, the average width being 19 inches. While ovens having a capacity of 13½ tons are in successful operation, some engineers advise limiting the size to 12½ tons. The oven, or retort, usually tapers about 4 inches, being widest at the discharge end. This provides room for the coal to swell and there will be less resistance offered to the moving of the coke. The ends of many ovens are closed by iron doors lined with firebrick, which fit closely and are luted with clay. In the latest ovens, the doors are plug-shaped and go into the oven far enough to hold the coal at the level of the first flue. This arrangement prevents the formation of black ends, because of coal projecting beyond the flues. Like the beehive oven, the tops of the chambers have openings through which the coal is charged. The ovens are level and the coke is pushed out by means of mechanical devices. Sometimes the coke is watered inside the closed receptacle which causes the coke to retain its silvery appearance, but more often the quenching takes place as the coke is pushed from the oven into a car stationed at the discharge end of the oven.

Horizontal-flue Type. — In most horizontal-flue ovens, each oven in a battery is a separate unit so that its working is entirely independent of the others. The latest form of Semet-Solvay oven has six horizontal flues in each side of the coal chamber, while an 18-inch wall separates the ovens in the battery. After the oven is charged, the gas for the combustion is admitted to the flue by a burner at the end. The combustion starts in the top flue, as the gas and fresh air admitted through

each flue is just enough to maintain a uniform temperature. In order to allow for the greater volume of the products of combustion, the flues gradually increase in size until the bottom flue is reached; this is reduced in size as only a part of the products of combustion pass through it.

The gases from the coal chamber are carried to a condensing house where the by-products are removed. Part of the gas is then returned to heat the oven, while part may be used for lighting or power purposes. In a non-regenerative oven, the gases are wasted as soon as they pass through the oven flues. In regenerator ovens, the gases pass through the regenerator at the other end of the oven through which they were admitted, and heat its checker-work. Each oven in the latest type has a regenerator at each end, through which the air passes on its way to the flues. All the regenerators in a battery, which usually contains about 50 or 60 ovens, are operated at one time.

Vertical-flue Type. — In most vertical-flue ovens, adjoining coal chambers have one gas chamber between them. In the Koppers oven, the charge is subjected to a uniform heat, because there are thirty vertical flues in each side of the oven, which is, therefore, heated by the combustion of gas at sixty different points.

Recovery of By-products. — Ordinary Connellsville coal contains approximately 62.5 per cent of fixed carbon and 28.36 per cent of volatile matter. In other words, over one-quarter of the coal evaporates and passes off in the coking process. This volatile matter gives a gas that is rich in methane, or marsh gas, and hydrogen. The average composition of gas from the Semet-Solvay type of oven is as follows: Hydrogen, from 40 to 50 per cent; methane, 35 per cent; nitrogen, from 4 to 8 per cent; benzines, from 2 to 3 per cent; carbon dioxide, 1 per cent; carbon monoxide, 1 per cent; oxygen, 0.5 per cent. The calorific value of this gas averages 500 B.T.U. per cubic foot. Ovens, however, have been constructed that are so free from leaks that, for each ton of coal coked, they give off over 6000 cubic feet of gas having a value of 590 B.T.U. Besides, there is obtained tar

suitable for pavements and roofs, benzol, and ammonia. In addition, the yield of coke is greatly increased, one ton of coal giving 70 per cent of its weight in coke, in comparison with 60 per cent obtained in the beehive oven.

The amount of by-products recovered, however, varies with the nature of the coal used and the coking period. Under average conditions, a ton of coal in addition to its coke will yield 6000 cubic feet of gas; 7 gallons of tar; from 20 to 25 pounds of ammonium sulphate; and, if suitable apparatus is available, from 1.1 to 3.8 gallons of benzol, and 0.3 gallon of toluol. If the surplus gas is used for fuel purposes alone, only one gas main is necessary along the top of the oven. If the gas is used for illuminating, or for other purposes, two mains must be installed. One main is then used for the rich gas evolved during the first period of coking, and the other for the poorer or fuel gas. This separation is also made in many plants in connection with iron and steel works which desire a rich gas for their gas engines and a lean gas for the heating of furnaces, etc.

In the by-product plant, after the gas has cooled, the tar is extracted, naphthalene is "thrown down" as far as possible, and the ammonia is scrubbed out of the gas and passed through dilute sulphuric acid, so as to form sulphate of ammonia. In some plants, however, the gas is passed through a saturator after the tar has been separated, thus rendering the scrubbing of the ammonia unnecessary. The value of by-products recovered from American coke manufacture in 1915 was nearly $30,000,000. Although there were material increases in the output and value of gas, tar, and ammonia, the value of the benzol products rose from less than $1,000,000 in 1914 to more than $7,760,000 in 1915.

Flux used in Blast Furnace. — A flux is used in the smelting of iron ore in a blast furnace in order to make the non-metallic residue of the ore and ash of the fuel more fluid, so that they will flow out of the furnace in the form of slag. This slag must have such a composition that it will melt when it reaches the melting zone of the blast furnace, fluid enough to run out through the cinder notch, and rich enough in lime to supply the lime

needed for the desulphurizing reaction. The flux almost universally used is limestone, which is available in nearly all iron-making localities. Magnesia is also sometimes used. Dolomite, often called "magnesia limestone," has also been successfully used, but furnace men generally prefer limestone, as they claim that dolomite is not as active a desulphurizing agent as limestone. Some iron ores contain sufficient limestone or magnesia to form a fusible slag, but generally some additional flux is provided. The limestone or other fluxes are used in the condition in which they are mined. Limestone, if roasted, will more readily unite with impurities, but the cost of the treatment offsets any saving that may thus be effected. The amount of flux required depends primarily upon the silica in the flux and in the rest of the charge; for ordinary pig iron, using Lake Superior ores, about 1000 pounds per ton of iron may be taken as an average.

Effect of Various Elements on Pig Iron. — The manganese, phosphorus, silicon, and sulphur present in pig iron all have a different influence upon the characteristics of the iron. Sulphur and silicon tend to segregate in the iron and are, therefore, generally found unevenly distributed through it. The content of sulphur is likely to be found highest near the top of the pig. The presence of soft gray spots is an indication of the segregation of silicon. The remelting of the pig iron usually makes it more uniform in composition; hence, the remelting of the pig iron in the cupola furnace for making iron castings improves the metal in the pig.

Influence of Manganese. — In pig iron the content of manganese ranges from a trace to about 3 per cent. For pig iron intended for making castings, more than 1 per cent of manganese for light castings, or 2 per cent for heavy castings requiring strength, may prove injurious; but when used in moderate percentages it strengthens the iron, deepens the chill, and, in cupola work, assists in eliminating the sulphur. By this elimination of the sulphur, softer castings are obtained. Manganese increases the time required for the molten metal to solidify. The condition of the blast furnace determines to a large extent the

percentage of manganese in the pig iron, as a cold-working furnace will tend to pass off the manganese into the slag, while a hot-working furnace will pass it into the pig iron.

Influence of Phosphorus. — Phosphorus has a very decided influence on the castings made from pig iron. Over 0.75 per cent is likely to cause the iron to be cold-short and over 1.3 per cent will appreciably harden the iron. Phosphorus is present in pig iron in amounts ranging from a trace to 1.5 per cent. Pig iron having less than 0.1 per cent of phosphorus can be used for the Bessemer process. That having more than 0.1 per cent of phosphorus can only be used for the open-hearth process and for foundry iron. Phosphorus adds to the fluidity of the molten metal, but, when present in large percentages, weakens the metal more than any other element.

Influence of Silicon. — The permissible silicon content in pig iron depends upon the sulphur and manganese content. If the content of sulphur and manganese is low, that of silicon should be low, and unless the sulphur and manganese content is high, the pig iron should not contain more than 3 per cent of silicon. Additional silicon will produce castings that are brittle or "rotten short."

Influence of Sulphur. — Pig iron usually contains from 0.03 to 0.10 per cent of sulphur. Sulphur causes iron to be "red-short" as well as "cold-short," that is, the iron is brittle either when heated to a red heat or when cold. The sulphur in pig iron is mainly derived from the fuel in the blast furnace. On the one hand it increases the strength of the iron and makes it harder, but, on the other, it is likely to make light castings too hard and cause blow-holes. The amount of sulphur that pig iron absorbs from the fuel depends upon the condition of the furnace. A greater amount of sulphur is absorbed in a furnace that is working cold. A properly or hot-working furnace sends the sulphur into the slag. Generally speaking, in iron made with coke, the lower the silicon, the higher the percentage of sulphur. Charcoal is low in sulphur, and, hence, charcoal pig iron contains less sulphur than anthracite or coke pig iron, and is, therefore, superior for many kinds of castings.

Classification and Grading of Pig Iron. — Pig iron is classified and graded in so many different ways that it is impossible to give any uniform or consistent method of classification. In a general way, however, it may be said that there are three methods of classifying pig iron; (1) according to its composition; (2) according to its intended use; and (3) according to the method by means of which it has been manufactured.

Grading According to Composition or Fracture. — With regard to composition, which is the modern method of classifying pig iron, such terms as "high-silicon pig," "low-phosphorus pig," etc., are used to indicate some important consideration in the composition. In modern practice, the classification according to composition is made by chemical analysis, but up to comparatively recent years, the practice was to merely examine the fracture of a broken pig. When the silicon content is low and the combined carbon high, the fracture is white, but, when the silicon is high, the fracture is more silver-gray, and if the carbon is mainly in the form of graphite, the fracture is a dull gray. When graded in accordance with the fracture, the ordinary grades of pig iron are No. 1, No. 2, No. 3, "mill," and "white." Sometimes, when close grading is desired, intermediate grades are used; thus, No. 2X will be between No. 2 and No. 1 irons. No. 1 iron has a dark gray fracture and its grain has large and uniform crystals of graphite to the extreme edge. No. 2 is lighter in color and has a grain with smaller crystals. No. 3 iron is still lighter in color and is close-grained. *Mill iron* has a uniform dull gray color, and has no suggestion of grain; its color depends largely upon the amount of silicon present. *White iron* is chilled throughout the section, as nearly all the carbon is combined; it is high in sulphur and low in silicon.

Classification According to Use. — With regard to the use for which the pig iron is intended, there are a great many different names, such as foundry iron, malleable pig iron, chilling iron, Bessemer pig iron, basic pig iron, gray forge iron, ferrosilicon pig iron, mottled pig iron, and white pig iron.

Foundry Pig Iron. — Foundry pig iron is made either with coke or anthracite fuel, and is used for the making of both chilled

and unchilled castings. It generally contains from 1 to 4 per cent of silicon; from 0.01 to 0.05 per cent of sulphur; from 0.2 to 1.5 per cent of phosphorus; and from a mere trace to 1.5 per cent of manganese. *Softeners* are foundry pig irons which are high in silicon and usually high in phosphorus, and which are mixed with lower silicon irons or with mixtures that carry a considerable amount of scrap, in order to produce a soft casting. These pig irons contain from 2.5 to 5 per cent of silicon with from 0.2 to 0.3 per cent of phosphorus. *Malleable pig iron*, which is used for making malleable cast-iron castings, must contain less than 0.05 per cent of sulphur, while the phosphorus content may vary from 0.05 to 0.2 per cent; the manganese content, from 0.5 to 0.75 per cent; and the silicon content, from 0.6 to 1.25 per cent. *Chilling iron* is used for iron castings that require a hard surface. It is, therefore, low in silicon and high in sulphur. The latter element increases the chilling tendency, but the pig iron must not contain so much sulphur as to affect the strength of the casting when the strength is essential. As a rule, the silicon content generally ranges from 0.1 to 0.4 per cent with from 0.5 to 1 per cent of manganese. The phosphorus content must be less than 0.3 per cent.

Bessemer Pig Iron. — Bessemer pig iron is made with either coke or anthracite as a fuel, and is used chiefly for the making of acid Bessemer and acid open-hearth steel, although it may also be used as a foundry iron for heavy castings which do not require a very fluid metal. Bessemer pig iron contains from 0.75 to 2.5 per cent of silicon; from 0.01 to 0.05 per cent of sulphur; and from 0.2 to 1 per cent of manganese. It must not contain more than 0.1 per cent of phosphorus. If it contains a greater percentage than this, it is called "off-Bessemer." Pig iron is often classified as Bessemer and non-Bessemer iron, according to whether the phosphorus content is less or more than 0.1 per cent.

Basic Pig Iron. — Basic pig iron is used chiefly in the basic open-hearth furnace for making steel. This pig iron is cast in chilled molds or magnesia sand. It is similar in character to gray forge iron (see following paragraph) but its sulphur

content must not exceed 0.05 per cent.   In pig iron for the open-hearth process, the phosphorus should also be kept low, but need not be as low as in Bessemer pig iron.   It may range from 0.2 to 2.5 per cent.   The silicon content should be less than 1 per cent, and the manganese content may range from 0.3 to 1 per cent.

Gray Forge Iron. — Gray forge pig iron is used chiefly in the puddling furnace for making wrought iron and in the foundry for casting water pipes and similar castings, in which case it is sometimes mixed with pig iron having a higher silicon content. Gray forge iron has a gray fracture with little or no grain.   Its sulphur content varies from 0.03 to 0.2 per cent, and its silicon content, from 0.5 to 2 per cent.

Ferrosilicon Pig Iron. — Ferrosilicon pig iron, also known as "silvery pig iron," is made from ores containing silicon, and an excessive amount of fuel is used to produce high temperatures in the furnace.   Ferrosilicon pig iron may be made either with coke or with a mixture of coke and coal as a fuel.   It is used in the Bessemer and open-hearth processes to increase the silicon content.   It contains from 6 to 16 per cent of silicon.   It has a large, open grain and is often used as a "softener."

Mottled and White Pig Iron. — Mottled and white pig irons are used for hard chilled castings.   They are made with either coke, anthracite coal, or charcoal as a fuel, and usually contain a high percentage of carbon.   The percentage of silicon may range from 0.1 to 1 per cent; of sulphur, from 0.05 to 0.3 per cent; of manganese, from 0.1 to 1.5 per cent; and of phosphorus, from 0.3 to 0.5 per cent.

Spiegeleisen. — Spiegeleisen may be considered as a pig iron which is very rich in manganese.   It is used for increasing the manganese content in steel, in the Bessemer and open-hearth processes.   It contains from 10 to 25 per cent of manganese. The alloy known as "ferromanganese" contains from 70 to 80 per cent of manganese, from 6 to 7 per cent of carbon, with the remainder iron.

Scotch Pig Iron. — Scotch pig iron, which may contain from 3 to 5 per cent of silicon, is used as a softener, particularly when

castings with a high silicon content are required. This pig iron has a large open grain and is dark in color.

Classification according to Method of Manufacture. — With regard to the methods of manufacture, pig iron may be classified as *coke* pig, *anthracite* pig, and *charcoal* pig. As the name indicates, coke pig iron is smelted with coke; anthracite pig iron is smelted with anthracite coal mixed with coke; and charcoal pig iron is smelted with charcoal. This latter kind is superior to other brands of pig iron when melted in an air furnace. It is generally used for the manufacture of castings for guns, hydraulic and steam cylinders, and for chilled castings. It can be made freer from silicon, phosphorus, and sulphur than coke or anthracite irons. It generally contains from 0.5 to 2 per cent of silicon; from a trace to 1.5 per cent of manganese; and from 0.15 to 0.75 per cent of phosphorus. The sulphur content must not exceed 0.08 per cent. The silicon may sometimes be as high as 5 per cent. Charcoal pig iron is usually graded in a series of numbers which vary according to the silicon content, each number indicating an increase of 0.2 per cent of silicon.

CHAPTER IV

WROUGHT IRON AND ITS MANUFACTURE

IRON articles were, at one time, made by smelting the ore in an open hearth and hammering the pasty mass until most of the cinders and impurities were worked out. The metal was then beaten into the desired shape. The metal obtained in this way was wrought iron, and the quality of the metal in the articles produced by this method was excellent. The development of blast and cupola furnaces, however, made available the use of large quantities of molten iron, so that the more easily manufactured iron castings soon displaced the hammered metal for many purposes. Later, the development of the steel industry still more restricted the use of wrought iron. Nevertheless, a large field remains where its resistance to continued stress and the ease with which it can be welded renders it valuable. Where reliability is of prime importance, no material anywhere near within its price is superior to it. At present, wrought iron is used for spikes, nails, bars, nuts, wire, chain, crane hooks, horseshoes, sheets, plates, staybolts, piping, third rails, armatures, electromagnets, and in the manufacture of crucible steel. Years ago, marine engine shafting was invariably made from wrought iron. The firm of Blair of Stockton-on-Tees, one of the earliest makers of marine engines and one of the most conservative firms at the present time, still makes (or, at least, until very recently made) its shafting from this material. Two leading British makers of steam fire engines still use wrought-iron plates for their boilers. These boilers are capable of being subjected to very heavy duty in spite of their small size. In British locomotive practice, wrought-iron rivets are still used for the boilers.

Characteristics of Wrought Iron. — Wrought iron, chemically considered, is the purest form of commercial iron, as it contains a comparatively small amount of carbon, averaging about 0.1,

ranging from as little as 0.05 to 0.3 per cent. It contains, however, a considerable amount of slag mechanically mixed with it. Wrought iron is very malleable, and at a bright red heat it may be hammered or rolled into almost any desired shape, while at a white heat it can easily be welded. It is one of the most ductile of the metals, but unlike steel it does not harden to any appreciable extent when heated to a full red heat and suddenly cooled by quenching. It requires a higher temperature for melting than any of the other commercial forms of iron and steel, and the molten metal cannot be cast in a mold. When wrought iron is broken by tension or bending, a good quality of the metal shows a fibrous structure; but, if it is subjected to shock or continuous alternating stresses exceeding the elastic limit, the molecular structure becomes crystalline. Good wrought iron will not break suddenly unless the molecular structure has thus been transformed, but will give warning of excessive stresses by the gradual extension of the metal before breaking. Material that has become crystalline may be brought back to the fibrous condition by heat-treatment, generally known as "annealing"; crane chains, for instance, are thus frequently annealed in order to retain their original tenacity.

Wrought iron has a specific gravity of from 7.6 to 7.85. It melts at approximately 2700 degrees F., and has a linear expansion per unit length per degree F. of 0.0000065. Its electric conductivity is about one-sixth that of silver.

Strength of Wrought Iron. — As wrought iron is made in several different grades and qualities, definite figures as to its strength cannot be given, but it may be said in general terms that wrought iron has a tensile strength varying from 40,000 to 50,000 pounds per square inch; a compressive strength of from 40,000 to 45,000 pounds per square inch; and a modulus of elasticity of 27,000,000. The best grade of wrought iron has about the following physical characteristics: Ultimate strength in tension, 50,000 pounds per square inch; ultimate strength in compression, 50,000 pounds per square inch; elastic limit in tension, 30,000 pounds per square inch; elastic limit in torsion, 20,000 pounds per square inch; elastic limit in compression,

from 20,000 to 25,000 pounds per square inch; modulus of elasticity in tension, 28,000,000; modulus of elasticity in torsion, 12,800,000; elongation in eight inches, 20 per cent; and reduction of area, 30 per cent.

The strength of wrought iron is affected by its chemical composition, and the mechanical working and heat-treatment to which it has been subjected. Wrought iron has a well-defined yield-point in both tension and compression, which is from 2000 to 4000 pounds per square inch lower than the proportionate elastic limit. Beyond the yield-point, wrought iron acts as a plastic material which flows rapidly as the ultimate strength is approached. The ultimate strength in tension increases with the amount of carbon. It is estimated that iron very free from carbon has a strength of about 40,000 pounds per square inch. The strength of wrought iron increases with an increase of temperature up to about 500 or 600 degrees F., after which the strength rapidly decreases. The percentage of elongation decreases as the temperature is raised up to 300 degrees F., but increases above this point.

Classification of Wrought Iron. — Wrought iron is classified and graded in so many different ways that it is impossible to name any system that could be called standard. The simplest classification is that by which wrought iron is divided into two large classes according to the method by which it is made. Wrought iron made from charcoal pig iron is named *charcoal iron*. This is usually refined and double-refined by the methods that will be described later in this chapter. Wrought iron made from coke pig iron is known as *common iron.*

According to a second classification, wrought iron is graded into four different grades or qualities: 1. *Norway* or, more correctly, *Swedish* iron, which is very fibrous and used for the best class of work. This is made from pig iron produced from magnetite ore, low in phosphorus, and with charcoal as fuel in the blast furnace. Although it is frequently referred to as Norway iron, this wrought iron comes from Sweden, the well-known Dannemora iron being one of the best grades known. This iron is unusually free from sulphur and phosphorus, both of

which elements have an injurious effect upon the metal, sulphur making the iron *red-short*, that is, brittle when hot, and phosphorus making it *cold-short*, that is, easily broken when cold. 2. *Double-refined* or *best-refined iron*, which is the best American domestic iron and which is used generally in forging, welding, and machine work. 3. *Refined iron*, which is a good grade of domestic wrought iron. 4. *Common iron*, which is made either from pig iron or from wrought-iron scrap. This quality does not weld as easily as the other grades.

According to still another system of classification, wrought iron is graded into three classes — charcoal iron, puddle iron, and busheled scrap iron. *Charcoal iron*, as the name indicates, is made from charcoal pig iron. *Puddle iron* is the second grade, made from a good quality of coke pig iron. The puddle iron, in turn, is divided into either three classes, A, B, and C, or into *staybolt iron* and *merchant iron*. The *busheled scrap iron* is made from wrought-iron scrap which frequently contains pieces of steel; hence, it is not uniform, does not weld as readily as the other grades, and is not as reliable.

British wrought iron is classified according to its origin, as *Yorkshire* and *Staffordshire* iron. The Yorkshire iron is, in turn, classified as *Lowmoor* and *Farnley iron*. The Yorkshire iron is the best British quality of wrought iron produced, and is made in large quantities. The Staffordshire iron is of a lower grade and the demand for it is constantly decreasing on account of mild steel being substituted for it. The best Yorkshire iron costs about twice as much as low-grade Staffordshire iron.

Corrosion of Wrought Iron. — Wrought iron resists corrosion to a remarkable degree. At Delhi, in India, there is a monumental column made from wrought iron which is more than one thousand years old, and in various other parts of India, where the climate is exceptionally humid, iron made by the natives centuries ago is still in existence fully exposed to the climatic conditions. In England, there are some exposed wrought-iron hand-rails at the Epping church, near London, which are one hundred and fifty years old. The iron used in all of these cases was probably smelted with charcoal as a fuel,

puddled in small quantities, and by the use of high-grade ore; hence, the wrought iron would be of exceptionally high quality.

Peculiarities of Wrought Iron. — If a 1-inch bar of the best Yorkshire iron is nicked ⅛ inch deep all around, say, with a sharp set, and is then broken over the anvil with a single blow, the bar will break square. The fracture will be coarsely granular, resembling badly burnt steel, but the granular structure will be coarser. A bar nicked on only one side, and carefully bent with the nick a couple of inches from the edge of the vise or anvil, will show a gray silky fibrous structure, free from crystals. The reason for this peculiarity, which is found only in the best Yorkshire iron, has never been satisfactorily explained.

The lower grades of wrought iron make an apparent weld at almost a melting temperature as well as at low heat. With the better grades of iron, however, a heat between closer limits of temperature is necessary; hence, good wrought iron should be worked only by a competent blacksmith, who must give closer attention to his work than when handling the cheaper grades. The less the iron is worked at the weld, the better will be the job. Unnecessarily working a weld at a comparatively low heat, so as to make a good-looking job, may reduce the total strength of the weld several tons per square inch.

Manufacture of Wrought Iron. — In the manufacture of wrought iron, the processes used differ slightly according to the kind of wrought iron being made and the raw materials from which it is produced. As common wrought iron may be made either from pig iron or from scrap, it will be necessary to refer to the methods used in either case. Refined wrought iron is made by melting pig iron and puddling it in a puddling furnace in the same way as common iron, but the resulting product, in the form of bars, is subjected to a second heating and re-rolling, thus producing what is known as "refined" iron. Double-refined iron passes through the same processes as refined iron, but the bars thus obtained are again cut up, reheated and re-rolled. The double rolling of the metal makes it very fibrous, and this kind of material is extensively used in the construction of passenger and freight cars, because of its ductility and its capacity for

withstanding shocks and vibrations, in which regard it is much superior to steel. Sometimes the molten blast-furnace metal is charged directly into the puddling furnace, but, as a rule, pig iron is used as the raw material for wrought iron. The pig iron from which wrought iron is made generally contains from 3 to 5 per cent of carbon. As the carbon in wrought iron ordinarily does not exceed 0.25 per cent and generally is much lower than this, the excess of carbon must be removed during the puddling process.

Making Common Wrought Iron from Pig Iron. — The pig iron which is the raw material for making wrought iron is melted in a so-called "puddling" furnace where most of the silicon, carbon, phosphorus, and other impurities contained in the pig iron are separated from it, forming the puddle cinder. One type of puddling furnace is shown diagrammatically in the sectional and plan view in the accompanying illustration. The fuel is placed on the grate bars at A and the metal on the hearth at B. The hot gases of combustion pass over the bridge wall C and are deflected against the metal by the sloping roof D; then, passing over the rear bridge wall E, they go up the chimney F. Sometimes the hearth is made with a long slope toward the rear bridge wall and the pigs are piled upon this slope. As the iron melts, it runs into the depression at the center of the hearth where it is collected for "puddling." As pig iron melts at about 2100 degrees F. and wrought iron at about 2700 degrees F., the temperature in the puddling furnace is so gaged that it is high enough to melt the pig iron, but not high enough to keep wrought iron in a liquid state. Therefore, as soon as the small particles of iron become purified they partly congeal or "come to nature," forming a spongy mass in which small globules of iron are in a semi-plastic state.

Previous to this stage being reached, the impurities in the iron have been reduced in three stages. Most of the silicon and manganese and some of the phosphorus are removed in the "melting" stage; more of the phosphorus and some of the sulphur are removed in the "clearing" stage; and the oxygen and most of the remaining phosphorus and sulphur are removed in the "boiling"

stage. The purer the iron, the higher is its melting point, so that, as the molten iron is purified, it naturally becomes pasty. When this pasty condition is reached, the iron is puddled or stirred by long rods for about an hour. During this time the carbon and other impurities are oxidized by coming constantly in contact with the oxygen of the air. The carbon monoxide that is liberated burns in jets of blue flame known as "puddlers' candles." At this stage, the slag begins to sink or "drop," and granules of wrought iron gradually increasing in size appear on the surface of the metal as it congeals or "comes to nature."
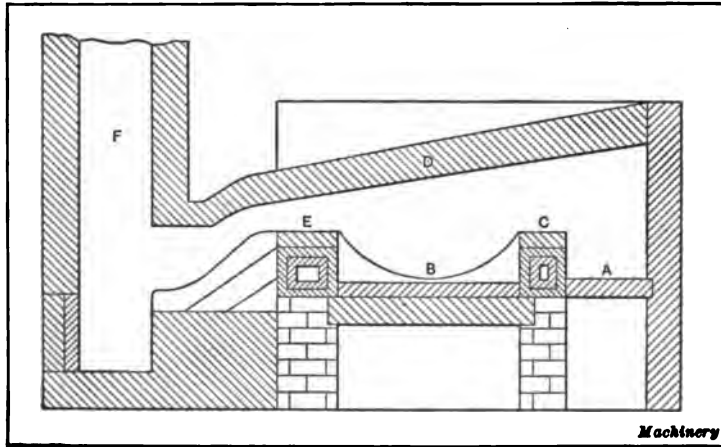
Sectional View of Puddling Furnace

The objects of the agitation or "puddling," which is accomplished chiefly by a long rod called a "rabble" which the puddler introduces through a notch in the furnace door, and which is assisted by the boiling of the metal, are (1) to produce as uniform conditions as possible throughout the bath; (2) to break up the larger masses of iron that tend to form; and (3) to prevent, as far as possible, the settling of the iron in a partly refined condition on the relatively cold bottom. The more fluid the metal, the more active must be the agitation, and the finer will be the grain of the resulting iron.

When puddled, the mass is divided by the puddler into puddle balls or lumps of about from 60 to 100 pounds each. The

balls or lumps formed by the puddler are shaped into elongated
blooms in a rotary squeezer, and while still hot are rolled out
into bars known as "muck bars." In American practice, these
bars are from 3 to 6 inches wide, ¾ inch thick, and from 15 to
30 feet long; their size compares with the size of the bloom
in the ratio of about 8 or 9 to 1. The muck bars are now cut
into pieces of from one to four feet (in American practice gener-
ally 3½ feet) in length, and are stacked in piles varying in weight
from 100 to 2000 pounds. These piles are placed in a reheating
furnace, and when white hot are taken to the rolls to be rolled
out and welded together. At this time, the wrought iron may
be rolled into bars, sheets, plates, or structural shapes. The
second rolling produces a more uniform material. When cold,
this material is sheared and straightened, and is then ready for
the market.

After leaving the puddling furnace, wrought iron does not
undergo any material change in its chemical composition, and
the only physical change is an expulsion of a large portion of
the cinder; the small cinder-coated globules of iron are welded
together, and the subsequent rolling back and forth elongates
these globules, giving the iron a fibrous structure, and the re-
heating and re-rolling drive these fibers closer together, thus in-
creasing the strength and ductility of the metal.

The work of making wrought iron by the puddling process sub-
jects the puddler to severe physical strain. He is exposed to
intense heat, and at the same time must perform hard physical
labor in stirring and moving the heavy lumps of iron. Ma-
chines have been devised for doing this work, but have not been
successful, and it is still performed in a manner very similar to
that in which it has been done for centuries.

Making Common Wrought Iron from Scrap. — Common
wrought iron may be made from wrought-iron scrap composed
of old horseshoes, bolts, bars, etc. Frequently this scrap also
contains pieces of steel, but this lowers the quality of the product.
The scrap is piled together and put into a heating furnace where
it is heated to a white heat — a heat high enough to temporarily
hold the pieces of scrap together. It is then run through rolls

and formed into flat bars which are cut up into the required lengths, three bars being placed together to form the sides and bottom of what is known as a "box," temporarily held together by U-shaped irons. Scrap iron is now put into this box and another bar is placed on top to complete the box, after which the sides of the box are fastened together with iron bands. These boxes which are known either as "box-piles" or as "faggots" are stacked up into large piles, usually by placing four in one direction and four crosswise in another direction. These piles are heated to a white heat in the furnace and then each box-pile is passed through the rolls to make the finished wrought iron. As the flat bars forming the sides of the pile have been rolled once, they have a denser grain than the center, which is composed of the scrap iron that has not been rolled before. The finished bars, therefore, have a fairly good surface, but they are not homogeneous, and scrap wrought iron is not as good as that made directly from pig iron by the puddling process. Furthermore, as the scrap material is not uniform in quality, the quality of the product varies. Common wrought iron made from scrap is also known as "busheled iron." It should not be used when a first-class product is required.

Other Processes for Making Wrought Iron. — In addition to the puddling process, there are several processes, known as *charcoal-hearth* processes, in which the wrought iron is made by methods somewhat different from those used in puddling. One of these is the "finery" process, which is employed for making the best Yorkshire iron. Another is the "Walloon" process, which is employed in Sweden for making wrought iron from Dannemora pig iron, and a third is the "Lancashire" process, which is also principally used in Sweden, but also to some extent in the United States. The highest grade of wrought iron is made by the charcoal-hearth process, although the puddling process is by far the most common method and produces the largest quantities of wrought iron. The essential difference between the two processes is that, in the charcoal-hearth method, atmospheric air supplies the oxygen for oxidation, and the fuel is burnt in contact with the iron, while in the puddling process

the chief source of oxygen is magnetic oxide of iron, and the fuel is burnt in a separate chamber from that containing the iron.

Manufacture of Yorkshire Wrought Iron. — Yorkshire wrought iron is manufactured by a process known as the "dry" process, similar in some respects to the puddling process, as described, but previous to applying this process, the pig iron is subjected to a special treatment. The process, which was introduced over a hundred years ago, is now infrequently used except for the class of iron mentioned. In this process, only white pig iron is employed. In order that the charge for the charcoal-hearth furnace shall be uniform, the pigs are first placed in a "refinery" furnace, in which the pig iron is first melted down in a coke or charcoal fire in order to remove the silicon, phosphorus, and sulphur, and to change what graphitic carbon may be present into the combined form. The metal is then transferred in a molten condition to the charcoal-hearth furnace, after which the process proceeds as follows: The furnace is charged with damp charcoal and a low-pressure unheated blast is used, the metal being puddled in a similar manner as in the puddling furnace, to make all parts of it come in contact with the blast. The puddling proceeds for about an hour, the same as in the puddling furnace, after which the metal is formed into balls and treated the same as puddled iron. In some cases, the iron and slag are tapped out of the furnace together, instead of being fed directly to the puddling furnace, the iron solidifying in molds in the form of thin slabs which are sprayed with water to quicken the cooling, and which are then broken up and charged into the charcoal-hearth furnace.

The Walloon Process. — In the Walloon process, a charcoal fire is used into which long pigs are gradually pushed, so that they slowly melt on the forward end. As the iron melts, it falls drop by drop through the blast and collects in a pasty mass at the bottom of the furnace. When dropping through the blast, it is decarburized. The pasty iron mass, which is partially refined, is then raised to the top of a charcoal fire, where it is melted in the presence of slag and hammer scale. From this point on the process resembles that of the puddling process.

Lancashire Process. — In the Lancashire process, the pig iron is melted between two layers of charcoal, and as the iron becomes liquid, it drops down through the blast and is decarburized in a manner similar to that of the Walloon process, the molten metal collecting in a pasty mass at the bottom of the furnace. After having remained there for from twenty minutes to half an hour, it is melted down with hammer scale and slag the same as in the Walloon process.

Defects in Wrought Iron. — The principal defects of wrought iron are rough places, "spilly" places, blisters, and excess of slag. Rough places are due to careless workmanship, imperfection in the rolls, and red-shortness. Spilly places are spongy or irregular spotted parts, and are particularly noticeable in sheets, although sometimes present in all kinds of wrought iron; they are generally attributed to imperfect puddling. Any impurities that may be present in wrought iron also greatly influence its properties. Silicon tends to produce hardness and brittleness, and if 0.35 per cent is present, the iron will be cold-short and deficient in strength. Phosphorus also will render it cold-short, if 0.25 per cent is present. If 0.03 per cent of sulphur is present, red-shortness is caused.

Testing Wrought Iron. — In testing wrought iron, the tensile strength varies according to whether the iron is tested "with" or "across" the grain; that is, "with" or "across" the direction of rolling. In testing steel, this condition need not be considered, as the strength in either direction is practically equal. The strength of wrought iron in bending or flexure also varies according to whether the bending is "with" or "across" the grain. Wrought iron is tested in a number of different ways in order to determine not only its strength, but its forging qualities and other characteristics. The United States Navy Department specifies that it should be possible to bend wrought iron cold to an angle of 180 degrees over a diameter of one thickness. In addition, it is subjected to tests for tensile strength, elongation, and reduction of area, as well as "nick" and "drift" tests. The nick test consists in nicking the bar approximately 20 per cent of its thickness and bending it back at this point to an angle of

180 degrees. It must then show a clean fiber, free from slag and dirt, and free from any coarse crystalline spots. A few crystalline spots may be tolerated, provided they do not, in the aggregate, exceed 10 per cent of the sectional area of the bar. The drift test consists in punching and expanding the bar by pointed drifts until a round hole is formed, the diameter of which is not less than 0.9 of the diameter of the rod or the width of the bar. Any indication of fracture, cracks, or flaws developed by this test will cause the rejection of the material.

Ram's-horn Test. — The so-called "ram's-horn" test was commonly applied in past years, and is still used in many places. It is a satisfactory test for indicating the forging qualities of wrought iron. To make this test, a hole about one and one-quarter times the size of the bar or the thickness of the plate to be tested is drifted hot from the solid, leaving the same distance clear from the end or the side. When testing a bar, the metal between the hole and the end of the bar is then split with a sharp set from both sides and turned over sideways. The name of the test is derived from the appearance of the test piece after this bending has taken place. Bars up to a sectional area of about two square inches may be tested in one heat, but larger sections require two heats, and frequently two heats are used for smaller sections also, in which case a second hole of the same size as the first is drifted lower down the bar at right angles to the first. When flat plates are tested, one horn is turned sideways and the other forward. When cold, the test specimen should show no defects and the surface of the ram's-horns should be free from cracks. It is necessary to use a clean fire and considerable speed in performing this test, as otherwise the metal may be injured by the manipulation, although it is of good quality otherwise.

Tests on Iron for Different Purposes. — Boiler plate should be subjected to tensile tests, hot and cold bending tests, and hot drifting tests. Wrought iron for rivets should be subjected to tensile tests, hot and cold bending tests, and upsetting tests. Staybolt iron should be subjected to an endurance test by threading the ends of an 8-inch specimen and fixing one end while the

other end is revolved in a circular path $\frac{3}{16}$ inch in diameter.
While revolving, the iron should be stressed with a tensile stress
of 4000 pounds per square inch, and should then be capable of
making at least 6000 revolutions without cracking or breaking.
Wrought-iron wire is tested by tension, bending, and torsion
tests. The bending tests are made in a hand vise the jaws of
which have a radius of curvature equal to twice the diameter of
the wire. The quality of the metal is shown by the number
of times that it can be bent without cracking or breaking.

Tests Indicating Quality of Iron. — The reduction of area is
the typical test that determines more accurately than any other
the real quality of wrought iron and hence bears a direct relation
to its price. The best Yorkshire bar iron has been known to
have a reduction of area of 60 per cent, and usually exceeds 50
per cent, while ordinary wrought iron seldom has a reduction of
area as high as 30 per cent. Two grades of wrought iron may
have approximately the same tensile strength and the same
percentage of elongation, but the reduction of area will indicate
which is the better quality.

Specifications for Wrought Iron. — Two grades of wrought
iron are specified by the U. S. Navy Department. Wrought
iron of the best quality required for naval use should have a
minimum tensile strength of 48,000 pounds per square inch;
a minimum elongation of 26 per cent; and a minimum reduction
of area of 40 per cent. It is further specified that the phos-
phorus content must not exceed 0.1 per cent, nor the sulphur
content 0.015 per cent. For ordinary blacksmith-shop use, the
Navy Department requires wrought iron having a minimum
tensile strength of 45,000 pounds per square inch; a minimum
elongation of 25 per cent; and a minimum reduction of area of
40 per cent for round bars, and 35 per cent for flat shapes. The
phosphorus content must not exceed 0.15 per cent, nor the sul-
phur content more than 0.02 per cent.

Wrought-iron Chain. — One of the most important uses for
wrought iron, at the present time, and one to which no other
material lends itself as well, is for the making of chain. The
reason for this is two-fold: In the first place, it is possible to

weld wrought iron with the assurance of obtaining a better weld
than any other material, and, second, good wrought iron, when
overstressed, gives warning by yielding or elongating, before it
actually breaks. A well-made chain, when subjected to a ten-
sile test, does not break at the weld, but always at the end of the
link that is not welded, or at the side. A break at the weld in-
dicates lack of skill or carelessness in the production of the chain.
Chain that is made from the best quality of iron stiffens when
subjected to a breaking stress, so that it becomes practically
solid, like a piece of bar iron. Chain made from common wrought
iron does not show this peculiarity; hence, it may be used as a
test of the quality of the iron in the chain. Any chain which,
when in use, indicates a lack of freedom of movement has been
overstressed, and should not be used.

Difference between Wrought Iron and Low-carbon Steel. —
While chemically there is not much difference between wrought
iron and low-carbon steel, there is considerable difference in
their physical structures. Owing to the globules of pure iron
being coated with cinder in the puddling furnace, the subsequent
rolling and reworking, while expelling a large portion of this
cinder, always leaves a trace of it behind which gives wrought
iron the fiber. As steel is produced in a liquid form and the
cinder floats to the top and is removed, the metal is without any
grain or fiber. When subjected to many vibrations, or strains
due to frequent expansion and contraction, wrought iron will
generally yield gradually and give warning, while steel is more
liable to snap off suddenly. The fibers of wrought iron can break
one at a time without directly affecting its neighbor (like the
strings in a rope), but if a rupture is once started in steel, it will
extend more rapidly.

Wrought iron will also resist corrosion and pitting longer than
steel, no doubt due to the higher resisting power of the enclosed
cinder, which also causes the acid to deflect endwise, thus weak-
ening its action by diffusing it over a larger area and preventing
deep pitting. Staybolts and boiler tubes for locomotives have
proved more satisfactory when made of wrought iron than of
steel. Thin sheets, tin plate, corrugated iron covering, wire

fencing, pipes, oil-well casings, etc., have also proved much more durable when made of wrought iron than when made of steel. On the other hand, in rails, tires, guns, armor plate, etc., steel has proved far superior to iron, owing to its greater strength and hardness; corrosion is also here of minor importance, owing to the rails, etc., generally being worn out long before corrosion has a chance to affect them seriously. When structural steel or iron is used for bridges, etc., it is necessary to protect the metal from serious corrosion by frequent and careful painting; in the skeletons of high office buildings and other sky-scrapers, when completely covered with concrete, etc., so as to thoroughly exclude air or moisture, steel as well as iron will probably last indefinitely. Where material is buried in the ground, or exposed to the weather without the careful protection of paint, or where moisture has access to it by other channels, as in the interior of of pipes, wrought iron will outlast steel by a good margin.

Open-hearth Iron. — Some manufacturers are offering " open-hearth iron" as a substitute for wrought iron, and claim certain properties, such as resistance to corrosion, etc. Open-hearth iron is made in the open-hearth furnace at a high temperature, and is, therefore, considerably overheated in the manufacture. When used in the form of sheets, this overheating is probably rectified in the subsequent annealing, but, in bars, the material possesses a coarse structure and shows what is known as a "fiery fracture." The working temperature of open-hearth iron is comparatively limited. It must be worked at a comparatively high heat which produces the coarse crystalline structure. When the temperature falls below this point, the iron is brittle and is, therefore, not susceptible to mechanical working. Open-hearth iron should not be used as a substitute for wrought iron, except for sheets and other parts where final annealing of the material is possible. A sample of this iron was found to contain 0.07 per cent of carbon; 0.03 per cent of manganese; 0.006 per cent of phosphorus; and 0.02 per cent of sulphur.

Specifications for substitutes for wrought iron have been issued by the U. S. Navy Department, which for certain purposes permits the use of extra soft steel instead of wrought iron,

requiring, however, that the phosphorus content in such steel must not exceed 0.04 per cent; the sulphur content must not exceed 0.04 per cent; and the carbon content must not exceed 0.12 per cent. The specifications further require a minimum tensile strength of 45,000 pounds per square inch and a maximum tensile strength of 55,000 pounds, with a minimum elongation of 28 per cent, and a minimum reduction in area of 48 per cent. The elongation for rods or bars $\frac{1}{2}$ inch in diameter or less is measured on a length equal to eight times the diameter or the thickness of the section tested. Sections over $\frac{1}{2}$ inch, but less than $\frac{3}{4}$ inch, in diameter or thickness, are measured on a length of 6 inches, and sections above $\frac{3}{4}$ inch, in diameter or thickness, are measured on a length of 8 inches. The elastic limit must not be less than one-half the ultimate strength of any specimen. The steel, when scarf-welded and subjected to a cold bending test at the center of the weld, consisting in being bent flat to 180 degrees, must not show either cracks or flaws on the outer curve of the bend.

Distinguishing Wrought Iron from Steel. — Wrought iron may be distinguished from soft steel by cleaning it of scale and grease and immersing it for from 15 to 20 minutes in a mixture consisting of 3 parts of sulphuric acid and 1 part of muriatic acid, mixed with nine parts of water. The acids are poured into the water, and the mixture allowed to cool before it is used. After the sample is removed from this solution, it should be rinsed with water. The fibrous structure of the wrought iron should then be apparent; as steel has a crystalline structure, it will dissolve uniformly and show no fiber. Most wrought iron can also be distinguished from steel quite easily when turning or planing it, on account of the fibrous structure.

CHAPTER V

CLASSIFICATION AND CHARACTERISTICS OF STEEL

STEEL may be defined as an alloy of iron and carbon, together with small percentages of a number of other elements, such as manganese, silicon, sulphur, and phosphorus. So-called "special" or "alloy" steels also contain small percentages of some other metal, such as nickel, chromium, vanadium, tungsten, etc. According to the definition adopted by the Brussels Congress of the International Association for Testing Materials, held in 1906, steel is defined as "iron which is malleable at at least some one range of temperature, and, in addition, is either cast into an initially malleable mass, or is capable of hardening greatly by sudden cooling, or is so cast and so capable of hardening." Originally, the term "steel" referred only to what is now generally known as *high-carbon steel* or *tool steel*, which possesses, in an exceptionally high degree, the quality of hardening when being heated to a certain temperature and quenched in a cooling bath. Later, when the open-hearth and Bessemer processes were developed, the products of these processes were also termed "steel," although a Bessemer or open-hearth steel with a comparatively low carbon content differs in its properties and general characteristics from a high-carbon tool steel even more than a low-carbon or mild Bessemer or open-hearth steel differs from wrought iron. Strictly speaking, therefore, an entirely new term ought to have been used for the product produced by the new processes. Those who developed the processes, however, were anxious to call the product " steel," and so this name has been adopted for a large range of metal having carbon contents varying all the way from 0.10 to 2.0 per cent, and physical characteristics so different as to suggest entirely different metals.

In steel which does not contain any other metal, such as nickel, chromium, tungsten, etc., the characteristic element which

changes its properties in the most marked way is carbon. The amount of carbon is given either in percentage or in "points." A point is a one-hundredth of one per cent of the whole mass of steel, by weight; thus, for example, a 30-point carbon steel contains 0.30 per cent of carbon. The same system may be applied to the percentage of other elements present in the steel; for example, a steel containing 3½ points of sulphur would be a steel having a sulphur content of 0.035 per cent.

Classification of Steel. — There are a great many different methods according to which steel may be classified. With regard to the methods of production, it may be classified as "crucible" steel, which is made by the crucible process; "Bessemer" steel, which is made by the Bessemer process; "open-hearth" steel, which is made in the open-hearth furnace; and "electric" steel, which is made in the electric furnace. With regard to the carbon content, steel may be classified as "mild" or "low-carbon" steel — sometimes also known as "machine" or "machinery" steel — which does not harden appreciably when heated and suddenly cooled, and which generally does not contain more than 0.25 per cent of carbon; "medium" steel, which contains from 0.30 to 0.60 per cent of carbon, and which becomes perceptibly harder by being heated and quenched, but which is not hard enough to use for cutting tools; and "high-carbon" steel, which contains anywhere from 0.65 to 1.55 per cent of carbon, and which possesses the property of hardening to a marked degree when heated and quenched. This steel is often termed "tool steel," because of being suitable for cutting tools, files, etc. There is, however, no distinct line of demarkation between these different varieties, as they merge gradually into one another. Generally speaking, mild and medium steels are made by the Bessemer or open-hearth process, while high-carbon steel is made by the crucible and electric processes. While the best high-carbon steel is made by the latter processes, it is possible to make such steel by either of the other processes. In general, the Bessemer process produces the cheaper grades of steel, for rails and structural work. Most of the steel now used is made in the open-hearth furnace which pro-

duces a better grade of steel than the Bessemer. Open-hearth steel is used for boiler plate, bridge work, heavy forgings, etc. The crucible process produces a still higher quality of steel which is used for tools, small forgings, and high-class machine parts. The electric process is a competitor of the crucible process in the production of a high class of tool steel, and the former is also used to a limited extent in making some kinds of structural steel. All the varieties known as "steel" differ from both wrought iron and cast iron in one particular: they are all produced in a molten condition and are at once cast into ingots, which are afterwards rolled or hammered. Cast iron may be so cast, but cannot afterwards be rolled, while wrought iron may be rolled, but not cast.

From the metallurgist's point of view, steel may also be classified according to the number of elements besides iron that affect its characteristics. Steel is then divided into binary, ternary, and quaternary alloys. *Binary alloys* are steels that have one alloying element in addition to iron; since carbon is always present in alloys of iron, carbon steel is the typical binary alloy. *Ternary alloys* are steels that have two alloying elements, in addition to iron. Since carbon is invariably present, it is one of these elements. These steels take their name from the other elements, such as nickel steel, chromium steel, manganese steel, etc. The alloying elements may be present in any desired quantity. *Quaternary alloys* are steels having three alloying elements, in addition to iron; these elements may be present in any proportion. Carbon being one of these, the other two are shown by the name of the steel; thus, chrome-nickel steel, silico-manganese steel, etc.

With regard to the use for which steel is intended, it may be classified in many different ways, and a number of terms have become so thoroughly accepted in the iron and steel trade as to constitute distinct names for steels. Among these may be mentioned: Flange steel, machine steel, magnet steel, spring steel, structural steel, etc.

Steel may also be classified as "carbon steel" and "alloy steel," according to whether carbon or some other element has the greatest influence upon its characteristics. All steel in which

the carbon content is the chief factor in determining its characteristics is known as *carbon steel*. Alloy steels, or special steels, are those which contain some other metal besides carbon, which gives them some peculiar characteristic not possessed by ordinary carbon steel. Among the most important alloy steels are: Tungsten (also frequently known as "high-speed") steel, chromium steel, nickel steel, vanadium steel, and titanium steel.

When steel is melted in a furnace and cast in molds in a manner similar to that in which cast-iron castings are made, the product is known as "steel castings." The term "cast steel" should not be used in this connection, because cast steel originally was used to designate crucible steel, and while the term is now obsolete and little used, it is better to use the term "steel castings" rather than "cast steel," when steel cast in molds is referred to. *Semi-steel* is another grade of steel melted and cast in molds. It is produced by melting together cast iron with wrought iron or soft steel scrap.

Definitions of Terms used to Designate Steel. — The following alphabetical arrangement contains brief definitions of the most important names that are applied to different kinds of steel, and to steel used for different purposes:

Air-hardening steel is a tool steel containing, in addition to carbon, an element such as tungsten, so that the steel will harden by simply cooling in the air or by inserting the heated end in an air blast.

Alloy steel is a steel the properties of which depend principally upon some element other than carbon, such as nickel, tungsten, chromium, etc.

Bessemer steel is a steel of any carbon content made by the Bessemer process.

Blister steel is steel produced by impregnating bars of wrought iron or soft steel with carbon, by heating them in contact with carbonaceous matter.

Carbon steel is steel which owes its properties chiefly to various percentages of carbon; it is known as "carbon steel" to distinguish it from steels containing other elements which chiefly control the physical properties.

Cast steel is the same as crucible steel; the term "cast steel" is confusing and little used.

Cement steel is steel which is made by the cementation or converting process and is the same as blister steel.

Chrome or chromium steel is an alloy steel usually containing about from 0.30 to 2 per cent of chromium.

Converted steel is the same as blister steel.

Crucible steel is steel made by the crucible process, irrespective of the carbon content. It is sometimes called "cast steel," and, in England, "pot steel."

Damascus steel was formerly made at Damascus by some direct process; the steel was covered with beautiful designs and used principally for sword blades and gun barrels.

Electric steel is steel produced in an electrically-heated furnace.

Flange steel is a steel of such quality that it may be bent cold for forming flanges on sheets, etc.

Fluid compressed steel is steel which has been subjected to compression before the ingots were entirely solidified, in order to secure a perfectly solid and homogeneous mass.

High-speed steel is a term frequently applied to alloy steels, owing to the fact that metal-cutting tools made from them may be run at high speeds without losing their temper or hardness.

Machine or machinery steel is a steel containing about 0.20 per cent of carbon, and is intended primarily for casehardening.

Magnet steel is a term applied to tungsten steel when used for permanent magnets.

Manganese steel is steel usually containing from 11 to 14 per cent of manganese.

Molybdenum steel is a steel having properties which are quite similar to those of tungsten steel.

Nickel steel is a steel usually containing from 3 to 5 per cent of nickel.

Open-hearth steel is a steel made by the open-hearth process, irrespective of its carbon content.

Puddled steel is a slag-bearing steel made by the puddling process, which contains enough carbon to harden, when suddenly cooled; it is rarely, if ever, made at the present time.

Saniter steel is a steel made by the Saniter desulphurizing process.

Self-hardening steel is the same as air-hardening steel.

Semi-steel, which is used for making "semi-steel castings," by melting about from one-third to one-fifth (by weight) of wrought iron or soft steel scrap with cast iron, usually in a cupola, is also known as "toughened cast iron."

Shear steel is steel, usually in the form of bars, made from blister steel, by shearing it into short lengths, arranging in piles, and welding these piles by rolling or hammering at a welding heat. If this process of shearing, etc., is repeated, the product is called "double-shear steel." It is made principally in England and used for articles of cutlery, etc.

Siemens-Martin steel is steel made by the open-hearth process.

Special steels are steels which owe their properties principally to an element or elements other than carbon. These are also called "alloy steels."

Spring steel is a steel containing from 0.80 to 1.00 per cent of carbon, suitable for making springs.

Steel castings are unforged and unrolled castings made from any kind of steel, whether Bessemer, open-hearth, or crucible.

Structural steel is a grade of steel suitable in composition and shape of cross-section for structural purposes, and made in various grades, such as dead-soft open-hearth; soft Bessemer; soft open-hearth; medium open-hearth; and hard open-hearth.

Titanium steel is a steel which is given special properties by adding small percentages of titanium.

Tool steel is any kind of high-carbon steel suitable for making cutting tools.

Tungsten steel is steel usually containing from 5 to 18 per cent of tungsten, and from 0.4 to 2.0 per cent of carbon. It is extensively used for high-speed metal-cutting tools.

Vanadium steel is steel usually containing from 0.15 to 0.25 per cent of vanadium. It is also known as "anti-fatigue steel," owing to its unusual capacity for resisting repeated stresses.

Weld steel is iron containing enough carbon to harden if heated and suddenly cooled. The term "wrought steel" is also used.

Peculiarities of Steel. — If heated beyond a certain temperature, steel becomes burned and a permanent injury is done to the metal; hence, steel must be worked at a lower temperature and with greater care than wrought iron. For this reason, welds in steel cannot be relied upon with the same certainty as those in wrought iron, and the higher the carbon content, the less suitable is the steel for welding. Because of the lack of reliability of the welds, and also because steel is likely to rupture more suddenly than wrought iron, it has not been able to take the place of wrought iron for chain-making. Steel worked at a blue or black heat is injured more than if strained when cold. This property is known as "blue shortness." Steel is also affected by such action as shearing or punching, so that it is preferable to drill holes in steel plates rather than to punch them. The crushing stress exerted upon the edge of the plate in shearing has been found to have greater effect upon the quality of the metal in the case of steel than in the case of wrought iron.

Effect of Method of Working on Strength of Steels. — The strength of a steel depends upon the manner of working it as well as upon its chemical composition. If steel is not thoroughly worked it will be soft, weak, and not very tough. A plate 2 inches thick is not as strong and tough, proportionately, as a plate $\frac{1}{4}$ inch thick, because the thinner plate is much more thoroughly worked. Excessive working, on the other hand, lessens the ductility. For instance, the strength of a steel may be about doubled by drawing it into wire, but the ductility will be reduced to a very small fraction of 1 per cent. When steel is "cold drawn" or "cold rolled," as the process is frequently although erroneously called, its tensile strength may be increased as much as from 20 to 40 per cent and its elastic limit from 60 to 100 per cent; but its elongation is reduced. By this process the steel is given a hard skin or shell, but the core is unchanged.

If the steel contains a large proportion of carbon, the manner of cooling after working will also have a very important effect. Sudden cooling or "hardening" has an effect similar to that of cold working. The amount of the effect will depend upon the

proportion of carbon present, the temperature from which it was
cooled, the temperature to which it is cooled, and the length of
time in which the cooling takes place.

Distinguishing Various Kinds of Steel by Mechanical Tests.
— The best way to determine the quality and composition of steel
is by chemical analysis and by microscopic inspection. These
methods, however, are not available except in cases where a
properly equipped laboratory is at hand. A number of simple
methods may, however, be used to determine the quality of
steel with fair accuracy for general purposes. The simplest way
to distinguish between high-carbon and mild steel is by the ap-
pearance of a fresh break. High-carbon steel has a very fine
smooth fracture, while the fracture of soft steel is rough and
coarse. When a bar of high-carbon steel is broken, the fracture
is nearly silver-white, while the fracture of low-carbon steel is
more gray in appearance. If a bar of high-carbon steel and a
bar of mild steel are nicked all around and then placed on the
anvil with the nick directly over the edge of the anvil, the bar
of high-carbon steel will break at the nick when struck once or
twice with a sledge, but a bar of mild steel will require several
blows before it breaks.

If tools are hardened after being forged at the anvil without
any preliminary machining or grinding, the manner in which the
piece "scales" after hardening is an indication of its quality.
When heated to a cherry red, steel containing 1 per cent of carbon
will "scale off" evenly and leave a clean surface. Steel con-
taining 0.75 per cent of carbon will scale off in spots, leaving a
kind of speckled surface. Low-carbon steel will not scale off at
all, unless heated to a very bright cherry red or almost yellow.

Recognizing Steels by Their Sparks. — In a paper read before
Copenhagen Congress of the International Association for
Testing Materials, Max Bermann called attention to the fact
that the sparks given off when grinding iron and steel, by means
of emery wheels, present a different appearance according to the
kind of material ground. The path of the spark from its origin
to its extinction forms a line of light which, at the end, branches
out in every direction, having an explosion-like appearance.

This line of light may be called the "spark ray." It is the ends of these rays that, in particular, vary for different classes of steel, and which in the following will be called the "spark pictures." Some of these spark pictures contain only a very few lines; while others contain a great many, some of them presenting secondary explosions and projections, as if they were suddenly thrown out in various directions by an internal force.

With a carbon content of from 0.07 to 0.08 per cent, the number of the lines in the spark picture is from two to three. With an increase of the percentage of carbon, the number of the branching lines also increases. At low carbon contents, the lines
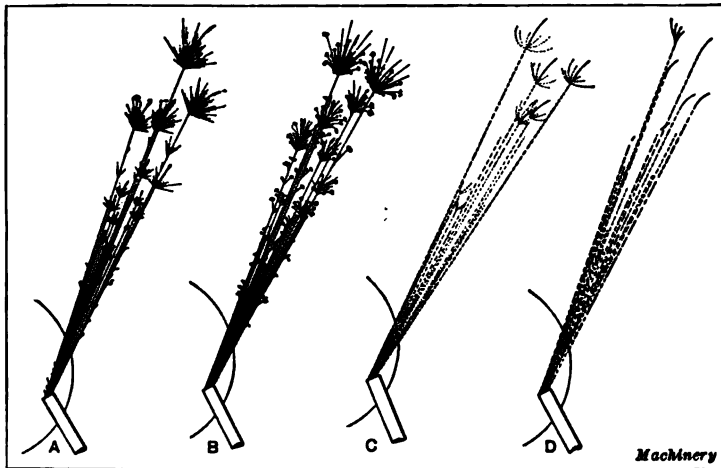
Fig. 1. Spark Pictures obtained from Different Kinds of Steel

appear to start from different points of the drop formation at the end of the ray, but when the carbon content is 0.25 or 0.27 per cent, the lines spring from a common point of the drop formation. The larger the carbon content the greater is the crowding of the lines projecting from the end of the ray, as shown at A in Fig. 1. In the case of tool steel, the spark picture resembles the branch of a blossom, and the individual branching lines have a lilac-like form.

The spark picture of steel containing manganese (as illustrated at B) shows at the end of the individual branching lines a sec-

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ondary explosion-like phenomenon, shorter lines collecting like
leaves around a common central point. The number of the
primary branching lines in this case also is in proportion to the
carbon percentage in the steel; the extent and shape of the
spreading ends of the primary branching lines appear to be in a
certain relation to the percentage of manganese contained by the
material.

The spark rays of steel containing tungsten (as shown at *C*)
are dark red lines, the ends of which show no spark picture if the
emery wheel is not sufficiently sharp and the pressure between
the wheel and steel is small. Only the very end of the ray has
a broader and more brightly glowing appearance, indicating
the beginning of a spark picture. If the steel is pressed more
firmly against the wheel, branching lines spring out in an ex-
plosion-like manner. These lines, however, take the form of
small shining pin-head-like balls. The spark sheave (a combina-
tion of spark rays and spark pictures) of chrome-tungsten high-
speed steel is distinct from that of the tungsten steel by the fact
that two kinds of rays appear, some very thin dark red and
some thicker brighter red ones, which are absent in the regular
tungsten steel. The spark pictures consist solely of short curved
drop forms.

The spark picture of nickel steel, containing less than 3 per
cent of nickel, is identical with that of carbon steel with a cor-
responding percentage of carbon. In case of larger percentages
of nickel, however, the nickel steel can readily be recognized
by the aid of the spark test, because the spark pictures show them-
selves in a sporadic manner, whereas, in the case of carbon steel,
they occur in close proximity and in close succession to one an-
other. Diagram *D* illustrates molybdenum steel.

Dark gray cast iron is characterized by fine dark red spark-
rays, spark pictures here and there, and lines collecting around
the drop formation like a net. The net-like lines disappear more
and more with the increase of assimilated carbon, and with
light gray cast iron they disappear altogether.

Application of Spark Test. — By means of the spark test,
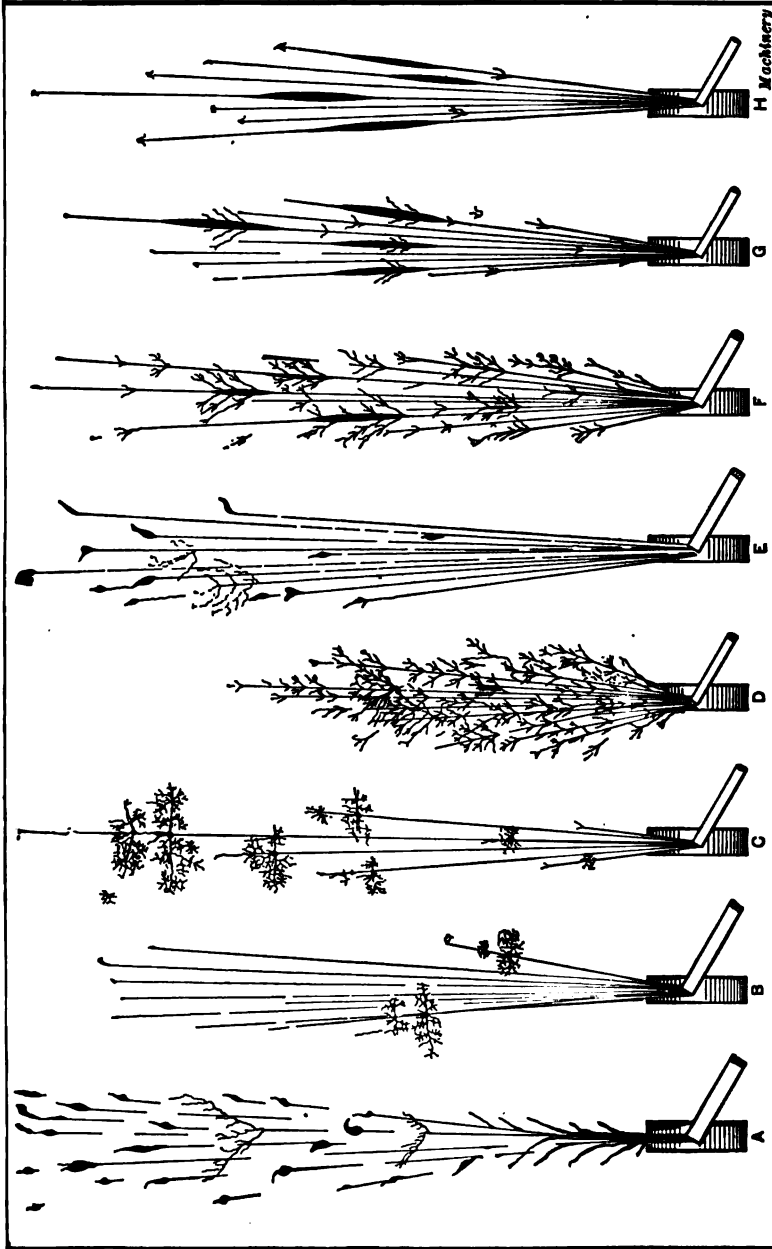different kinds of steel may be classified according to their carbon

Fig. 2. Characteristic Sparks of Different Steels as thrown off by a Grinding Wheel

percentage and according to the metals principally alloyed with them. The ends of rods that may have been wrongly arranged on the storing racks may, for example, be placed against a revolving emery wheel and the rods thus identified. The application of this method in the inspection of received material affords a rapid test for making sure that the material complies with the requirements. The test also supplies, in the hands of an experienced observer, a sensitive means of ascertaining differences in chemical composition at different places of the same bar or piece of material, it being possible to apply this test to both steel and cast iron. In the hardening room, by means of the spark test, it is possible to determine before hardening what grade and class of steel has been used for making the various tools, so that the proper hardening process may be applied. In the forge shop, the method may be of value for determining with certainty good malleable wrought iron.

In Fig. 2 are shown eight different spark pictures. These were originally shown in a paper presented before the Indiana section of the Society of Automotive Engineers, by John F. Keller. At A is shown a spark picture of wrought iron. The branching or forking of the luminous sparks indicates the presence of carbon. At B is shown a spark picture of mild steel, indicating a greater percentage of carbon than that present in wrought iron. At C is shown a spark picture of iron containing from 0.50 to 0.85 per cent, while at D is shown the spark picture of a high-carbon tool steel. The spark picture shown at E results from high-speed steel; at F, a spark picture of manganese steel; at G, one of Mushet steel; and at H, one produced by special magnet steel.

Determining the Hardness of Steel. — The hardness of steel and other metals may be determined by the sclerometer, the scleroscope, the Brinell indentation test, and the drill test. In the *sclerometer test*, a weighted diamond point is drawn, once forward and once backward, over the smooth surface of the material to be tested. The hardness number is the weight, in grams, required to produce a "standard scratch," which is one that is just visible to the naked eye as a dark line on a bright

reflecting surface. It is also the scratch that can just be felt with the edge of a quill when the latter is drawn over the smooth surface at right angles to a series of such scratches produced by regularly increasing weights.

In the *scleroscope test*, a small steel cylinder, with a hardened point and weighing about 40 grains, is allowed to fall upon the smooth surface of the metal to be tested; the height of the rebound of the hammer is taken as the measure of hardness. The height of the rebound of hardened steel is in the neighborhood of 100 on the scale, or about 6¼ inches, and the total fall is about 10 inches, or 254 millimeters.

In the *Brinell test*, a hardened steel ball is pressed into the smooth surface of the metal so as to make an indentation of such size as can be conveniently measured under the microscope. The spherical area of the indentation being calculated and the pressure being known, the stress per unit of area when the ball comes to rest is calculated, and the hardness number obtained. Within certain limits, the value obtained is independent of the size of the ball and of the amount of pressure. The standard diameter of the ball is (10 millimeters (0.3937 inch) and the pressure, 3000 kilograms (6615 pounds) in the case of iron and steel; for softer metals, a pressure of 500 kilograms (1102 pounds) is used. Of late, Brinell instruments have been so constructed that the microscope is not required.

In the *Keep drill test*, a standard steel drill is caused to make a definite number of revolutions while it is pressed with standard force against the specimen to be tested. The hardness is automatically recorded on a diagram on which a dead soft material gives a horizontal line, while a material as hard as the drill itself gives a vertical line, intermediate hardness being represented by the corresponding angle between 0 and 90 degrees.

Comparison of Hardness Testing Methods. — Each form of test has its advantages and its limitations. The sclerometer is cheap, portable, and easily applied, but the test is not applicable to materials that do not possess a fairly smooth reflecting surface, and the standard scratch is only definitely recognized after some experience.

The scleroscope test is simple, rapid, and definite for materials for which it is suited, but the results obtained vary somewhat with the size and thickness of the sample. As a comparative measure of the hardness of material of the same quality and structure, it is quite accurate, but it is not reliable for comparing the hardness of two different metals.

The Brinell test is especially useful for structural materials. It is definite and easily applied, but it cannot be applied to very brittle materials, such as glass, nor is it satisfactory for use on hardened high-carbon steel. For materials for which it is suited, the Brinell test also has the advantage that it may be used as a measure of the ultimate strength of the material. But there is no definite relation between hardness, as measured by the Brinell hardness testing method, and wear. While, in general, a high Brinell hardness number may be expected to indicate a metal that will give better wear, there are so many exceptions that this test for indicating wearing properties would be unreliable. For instance, Hadfield's manganese steel, which has a low Brinell hardness number, is one of the best steels as far as wear is concerned.

The Keep drill test is especially suited for castings of all kinds, as it records not only the surface hardness, but also the hardness of the whole thickness, and gives indications of blowholes, hard streaks, and spongy places. Obviously, it cannot be applied to materials too hard to be conveniently drilled by a hardened steel drill.

Microscopic Study of Steel. — The study of the appearance of steel under the microscope, showing what is known as the *microstructure* of steel has become one of the most important methods in studying the properties of steel, as well as other metals. The science of the microstructure of metal is known by metallurgists as metallography. By means of this microscopic study of steel, it is possible for the experienced metallurgist to determine many things relating to the composition and characteristics of steel. The magnified surface reveals the temperature at which steel has been hardened or tempered, and, in casehardened steel, the depth to which the hardness has pene-

trated. The carbon content can be closely judged when the steel is in the annealed state. The quantity of special alloying metals that are added to steel, such as nickel, chromium, tungsten, etc., can also be estimated. The microscopic examination also shows flaws and imperfections in the metal, and indicates the mechanical treatment to which it has been subjected, whether rolled, forged, slowly pressed into shape, or cast. In many cases, the microscopic study of steel shows, to the experienced observer, the various properties of iron and steel for industrial purposes which a chemical analysis would fail to reveal.

Method of Performing Microscopic Examination. — If a specimen of steel is to be examined under the microscope, it must first be properly prepared for this purpose. Steel as it leaves the manufacturer may be in a number of different states as regards its microstructure. In order to study it under the microscope it should first be annealed by being heated to about 1800 degrees F. and cooled very slowly. The different constituents will then appear in what is called the *normalized* state. A flat surface is then formed upon the specimen by filing or grinding, and this surface is then polished with successive grades of abrasives until a mirror-like polish is obtained. This surface is then etched with a suitable acid or etching reagent in order to reveal clearly the structure of the metal when the specimen is examined under the microscope. The etching acid acts unequally upon the different constituents, turning some darker than others, so that they can be readily distinguished under the microscope. The acid also cuts away certain of the constituents, making other parts stand out in relief. These raised portions resemble hills or plateaus in miniature and show white from the reflected light in the microscope; the portions that are cut away are valleys that receive no light, and, therefore, appear black.

Sometimes an etching acid or reagent is used that will color some of the constituents, so that they may be distinguished by their color. The basis of the three most commonly used etching reagents are picric acid, nitric acid, and tincture of iodine. The picric acid reagent is prepared as follows: Five grains of picric acid are dissolved in 95 cubic centimeters of absolute

alcohol, and the specimen to be etched is immersed in this solution for 30 seconds. The nitric acid reagent is prepared by mixing 10 parts of nitric acid with 90 parts of alcohol. The specimen is immersed in this solution for from 10 to 15 seconds. Tincture of iodine is used as a reagent by spreading one drop on each square centimeter of surface to be etched, and allowing it to remain on the surface until the specimen is discolored.

One of the constituents of steel, known as "cementite" (referred to in detail later), is not as easily attacked by the ordinary etching reagents as the other constituents, and, therefore, a different etching reagent is used. An immersion for 30 minutes in a 2-per-cent solution of oxalate of ammonium will give a red color to cementite, and a picrate of soda solution will give it a brown color.

In addition to the etching method for preparing the specimen, some specimens are prepared by "polishing in relief," which is done with a piece of parchment stretched over a smooth pine block. Rouge is rubbed firmly into the parchment and the latter is then rinsed over with running water so that only the rouge is left that has been forced into the pores of the parchment. The specimen to be tested is now rubbed over this soft surface, by means of which the softer elements in the specimen are ground out below the level of the harder elements. In this way, the harder elements which stand out will show white, while the softer elements that are ground out will show darker. A third method, known as "polish attack," which is a combination of the etching and polishing method, is also used. In this method a pine-wood block is covered with parchment the same as in the relief polishing method, but, instead of using rouge, the parchment is dampened with a solution of 2 parts of crystallized nitrate of ammonium in 98 parts of water. The specimen is then rubbed upon the parchment until the etching reagent has properly etched the surface.

When the regular etching reagents are used, the specimen to be etched is placed in a small porcelain receptacle just large enough to permit covering the specimen with the etching acid, which latter should be thrown away after being used once. Be-

for immersing the specimen in the etching solution, the surface to be etched must be perfectly clean and free from any trace of grease. It is also important that the etching solution comes in contact with every part of the surface to be etched immediately, as otherwise uneven and possible misleading effects may be obtained. Grease is most easily removed by washing the specimen before immersion with a dilute solution of caustic soda or caustic potash, or with ether.

As soon as the specimen has been etched, it is washed at once by rinsing in water or in alcohol, ether, or chloroform, in order to remove all trace of the etching reagent. After washing, the specimen may be quickly dried with a piece of cloth, or, if alcohol or some other volatile liquid has been used for the washing, the specimen may be dried by allowing a current of warm air to play upon the surface. This latter method is especially desirable, because it insures that the etched surface is not disturbed by the rubbing of the cloth.

Constituents of Steel as Revealed by Microscope.— A piece of low-carbon steel containing about 0.12 per cent of carbon prepared as described would appear under the microscope about as shown in Fig. 3. The dark grains are called *pearlite*. The white background is called *ferrite*, and consists principally of iron with a few impurities. In fact, ferrite may be considered as pure iron, and when carbon is added to it, each atom of carbon absorbs or combines with three atoms of iron. This carbide of iron is called *cementite*. Pearlite, again, is an intimate mixture of cementite and ferrite in the definite proportion of 32 parts of ferrite to 5 parts of cementite; hence, referring to Fig. 3, it will be seen that a piece of low-carbon steel, treated as mentioned, consists of a white background of iron or ferrite interspersed with a number of dark grains which consist also of some ferrite or iron in laminations or layers separated by laminations of carbide of iron or cementite, the combination of ferrite and cementite, as mentioned, being termed *pearlite*. In Fig. 4 is shown a steel containing 0.42 per cent of carbon treated in the same way. The difference is quite apparent. There is a much larger number of dark grains of pearlite, due to
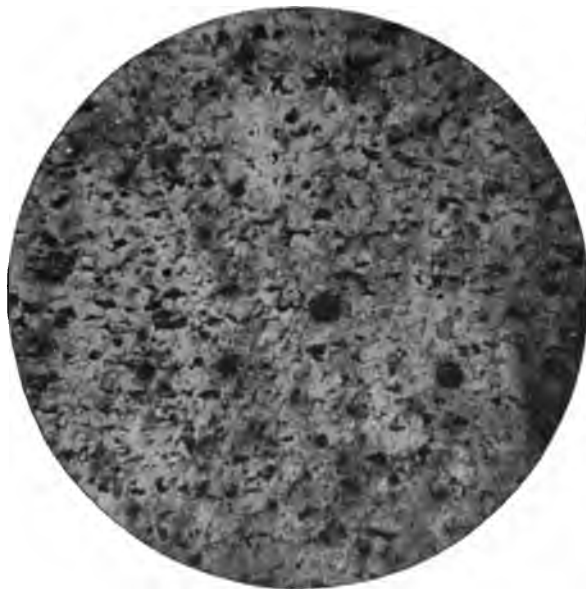
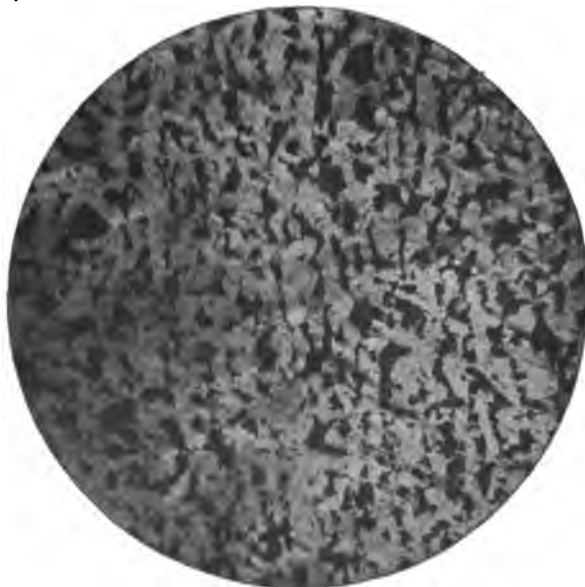Fig. 3. Steel, 0.12 Per Cent Carbon; Magnification, 300

Fig. 4. Steel, 0.42 Per Cent Carbon; Magnification, 300

the increase of carbon, and it becomes obvious that there must be a steel high enough in carbon content to be composed of all dark grains and have little or no white background; in other words, the steel is composed entirely of pearlite without any ferrite background. Such a condition, in fact, is reached when the steel contains from 0.80 to 0.90 per cent of carbon, and steel of this kind is known as *eutectoid* or *saturated* steel. Below this percentage, the surface shows pearlite and ferrite, and above this percentage of carbon, it shows pearlite and cementite. All steel with a lower carbon content is called *hypo-eutectoid* and all steel containing more than from 0.80 to 0.90 per cent of carbon is called *hyper-eutectoid*. In high carbon steel, the pearlite and cementite will be present until a carbon content of 6.6 per cent is reached, when the whole structure will be cementite. Fig. 5 shows the appearance of a steel containing 1 per cent of carbon, showing excess of carbide of iron or cementite in connection with pearlite.

Microscopic Study of Heat-treated Steels. — In heat-treated steels, the ferrite, pearlite, or cementite, which are the constituents of annealed or normalized steels, are replaced by other constituents. It is for heat-treated steels that the microscopic study is of especial value, as it makes it possible to determine the conditions under which the heat-treatment has been conducted and the results obtained. Assume, for example, that a piece of normalized steel containing the required amount of carbon for hardening is heated to about 1500 degrees F. and quenched in water. It will then become hardened. If polished, etched, and examined under the microscope, it will now show a very fine structure, apparently lacking in detail. In other words, the heat-treatment has caused the grains to become merged as if in a solution and, as a matter of fact, the condition is referred to by that name, the steel being said to be in a state of *solid solution*. Heating the steel to the temperature mentioned has allowed the solution to form, and the sudden cooling has arrested the steel in this condition. The constituent obtained in a steel that has been heated to the correct hardening temperature and quenched is known as *martensite*. While the steel is heated above
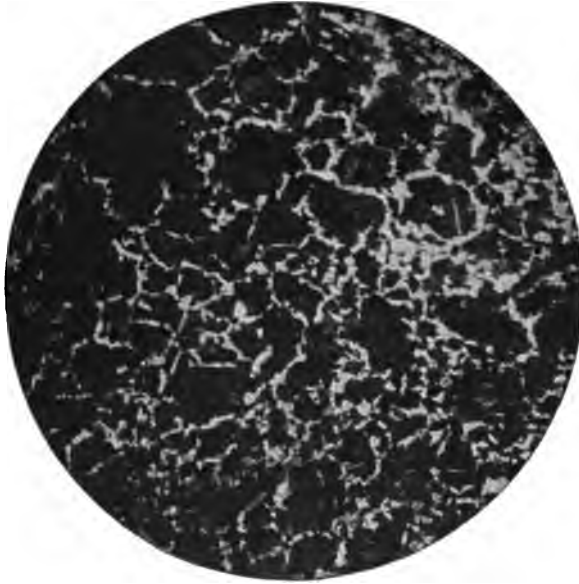
Fig. 5.   Steel, 1.00 Per Cent Carbon; Magnification, 100; Note Excess
of Carbide of Iron or Cementite

Fig. 6.   Left: Casehardened Steel, Core, 0.03 Per Cent of Sulphur;
Right: 0.06 Per Cent of Sulphur

the temperature required for hardening, it is changed to *austenite*, but does not remain in this condition when subjected to ordinary heat-treatment. If the steel is cooled suddenly, it changes to martensite as just mentioned, but in the case of large pieces of steel, the center is not affected by the heat-treatment as much as the outer portions, and another constituent known as *troostite*, usually intermingled with martensite, is developed. The martensitic structure of hardened steel is also changed into troostite by drawing the temper by reheating to a temperature below 750 degrees F. Finally, if the drawing temperature exceeds 750 degrees, a constituent called *sorbite* is developed, which reaches its maximum at about 1100 degrees F. Hardened steels, the temper of which has been drawn to temperatures between 750 and 1100 degrees F., show both troostite and sorbite and are known as *troosto-sorbitic* steels. When the drawing temperature does not reach 750 degrees F., some of the martensite is not transformed into troostite, and the steel is known as *troosto-martensitic* steel. When a drawing temperature of about 750 degrees F. is reached, the martensite has all disappeared, and this condition has been named *osmondite*, but as it is merely the boundary line between troostite and the next constituent sorbite, developed by the higher drawing temperature, it is doubtful if any definite constituent can always be located and named in this manner. If steel which is hot enough for hardening and is in the austenitic condition is cooled slowly, the martensite which is trapped or fixed by sudden cooling is not retained, but the steel finally changes back to pearlite or to the annealed condition.

Microscopic Study of Casehardened Steels. — If a piece of low-carbon steel has been carburized and is then annealed or normalized, polished, and etched, all the variations of carbon content from hypo-eutectoid in the core to hyper-eutectoid in the outer zone or case may be noticed by microscopic study. In Fig. 7 is shown a photo-micrograph which illustrates a portion of a casehardened bar from the outer edge inward, almost through the depth of the case. The outer zone is hyper-eutectoid, the light framework being cementite; there is then a

Fig. 7.   Outer Portion of Case; Magnification, 50

Fig. 8.   Continuation of Fig. 7 showing Core

eutectoid zone which consists of pearlite with practically no other constituent; and finally a hypo-eutectoid zone which consists of pearlite with light ferrite grains. The illustration, Fig. 8, is a continuation towards the core of the same piece as shown in Fig. 7, the light white line at the bottom of Fig. 7 corresponding to the line near the top of Fig. 8, this line locating the two photographs with relation to each other. If the two photo-micrographs were cut along these two white lines and joined, they would make a continuous view. In Fig. 8, when the core is reached, the ferrite grains predominate. Incidentally, Figs. 7 and 8 show an example of a specimen which represents a good carburization process. The case will be hard when heat-treated, and will adhere well to the core. By the study of photo-micrographs such as those referred to, valuable information as to the heat-treatment being given to steel in practical work may be obtained.

Fig. 6 shows another use for the photo-micrograph. Here, to the left, is shown a casehardened steel which contains 0.03 per cent of sulphur; to the right is shown one that contains 0.06 per cent of sulphur. The effect of increasing the sulphur content is very apparent, the grain being very much coarser. However, with the present knowledge of microscopic examination of iron and steel, no satisfactory test has been evolved for the determination of the sulphur content. It is merely possible to see the difference caused by different amounts of sulphur. The sulphur and phosphorus content, therefore, should be determined by chemical analysis.

Photo-micrographs of Iron and Steel. — Figs. 9 to 32, inclusive, show a number of photo-micrographs of iron and steel containing different proportions of carbon, and having been treated in different ways. Fig. 9 shows a low carbon specimen containing about 0.05 per cent of carbon; here ferrite predominates, with small areas of pearlite. Fig. 10 shows a sample having a carbon content of about 0.10 per cent. Figs. 11, 12, and 13 show samples with increasing carbon percentages, indicating also an increase in pearlite. Fig. 14 shows a steel having 0.90 per cent of carbon in which the pearlite area predominates.

Fig. 9.   Ferrite and Pearlite;
Carbon, 0.05 Per Cent
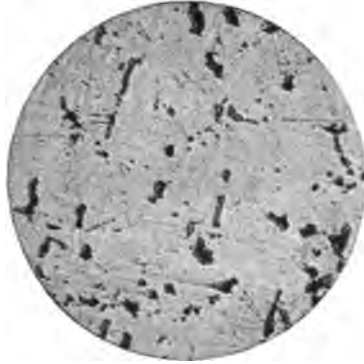
Fig. 10.   Ferrite with Pearlite Islands;
Carbon, 0.10 Per Cent

Fig. 11.   Ferrite and Pearlite;
Carbon, 0.16 Per Cent

Fig. 12.   Pearlite, 28 Per Cent;
Carbon, 0.25 Per Cent

Fig. 13.   Pearlite, 60 Per Cent;
Carbon, 0.54 Per Cent

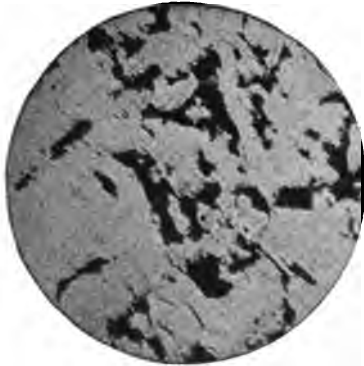Fig. 14.   Pearlite Area predominating;
Carbon, 0.90 Per Cent

Fig. 15.   Crucible Steel

Fig. 16.   Steel in Fig. 15, Hot-rolled

Fig. 17.   Steel in Fig. 16,
Cold-drawn

Fig. 18.   Steel quenched at Correct
Hardening Temperature

Fig. 19.   Steel quenched at 50 De-
grees C. above Correct Hardening
Temperature

Fig. 20.   Steel quenched at 100 De-
grees C. above Correct Hardening
Temperature

7 B
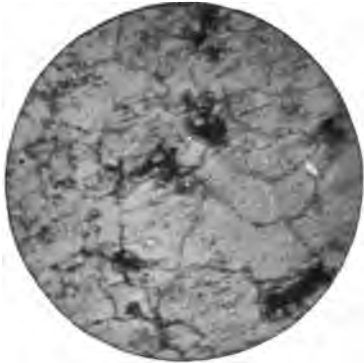
Fig. 21. Steel quenched at 200
Degrees C. above Correct
Hardening Temperature

Fig. 22.
Martensite Structure in a Fine-
grained Steel

Fig. 23. Martensite Structure in a
Coarse-grained Steel

Fig. 24. Troostite Structure; Steel
drawn at 250 Degrees C.

Fig. 25. Temper drawn at 400 De-
grees C.; Osmondite Structure

Fig. 26. Temper drawn at 550 De-
grees C.; Sorbite Structure

Fig. 27.   Quenching Oil too Hot;
Troostite and Martensite Structure

Fig. 28.   Crystalline Structure of
Overheated Steel
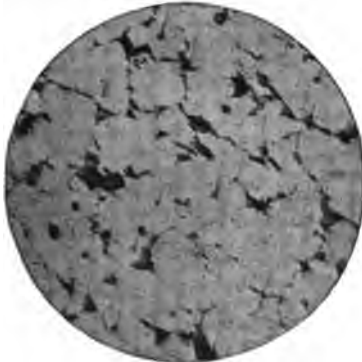
Fig. 29.   Steel of Fig. 28 restored
by Correct Heat-treatment

Fig. 30.   Burnt Steel showing
Cracks between Crystals

Fig. 31.   Casehardened Steel showing
Unequal Carburization

Fig. 32.   Crack between Carburized
Shell and Core

Fig. 15 shows the appearance of a crucible steel of comparatively high carbon content in its annealed and unworked condition. Figs. 16 and 17 show the same steel subjected to different kinds of mechanical treatment, and Figs. 18 to 21, the same steel heated and quenched at different temperatures. The change in structure, when the steel is heated above its correct hardening temperature, is very evident. Figs. 22 and 23 show the martensite structure of steel in a very satisfactory manner, while Figs. 24 to 26 show the structure in hardened steel drawn to different temperatures. Fig. 28 shows very clearly the coarse-grained crystalline structure of overheated steel, and Fig. 29 the same steel restored as nearly as possible to its finer grain by correct heat-treatment. Fig. 30 shows a burnt steel with cracks between the crystals, and Figs. 31 and 32, casehardened steel unevenly carburized and with a crack between the carburized shell and core.

Etching Reagents for Hardened Steel. — The etching reagents that can be used on annealed steel are not suitable for hardened steel. For the latter, good results are obtained by a solution composed of 4 parts of sulphur dioxide in 96 parts of water. The specimens are immersed in this with the face upward, and removed when the polished surface appears to be frosted, the time required being anywhere from a few seconds to one minute. They are then rinsed in water and dried in alcohol. This etching reagent gives different colors to the different constituents. Austenite is pale brown; martensite, from pale blue to brown; troostite, very dark; sorbite, uncolored; cementite, brilliant white; and ferrite, a dark brown. Various other etching reagents can also be used to give different colors to the various constituents.

Permeameter for Magnetic-mechanical Analysis. — Research work done abroad and at the U. S. Bureau of Standards has shown that the magnetic properties of iron and steel afford a most valuable index to the structural conditions existing in such materials, which is of special importance in those materials intended for use where strength or cutting properties are the essential factors. Not only do the initial processes of manufac-

ture affect the magnetic characteristics, but subsequent heat-treatment also; therefore, the magnetic test offers means of examining materials, tools, etc., during and after manufacture, without injuring or marring them, with a view to predetermining their mechanical performance.

The method of " magnetic-mechanical analysis" is based upon the fundamental fact that there is only one set of mechanical characteristics corresponding to a given set of magnetic characteristics, and conversely there is only one set of magnetic characteristics corresponding to a given set of mechanical characteristics. The International Association for Testing Materials, The American Society for Testing Materials, the U. S. Bureau of Standards, and a number of private investigators are actively engaged on this important work, so that the science of properly correlating the underlying factors will surely make rapid progress in the near future, especially since accurate and convenient apparatus has now been developed to permit the practical application of this method of analysis in the industries. There are many advantages of " magnetic-mechanical analysis" which are of great importance. The material actually entering into the construction of the finished product and, in most cases, the final product itself can be subjected to the test without suffering the slightest injury. The various methods of testing now largely used (chemical, microscopic, hardness, tensile, impact, etc.) are either destructive or local surface tests. A wholly different line of testing from that now employed is opened by these magnetic investigations; that is, the reaction of the material to forms of energy which have no permanent effect on the material itself. Besides the point of destruction, the important question of " sampling error" enters into all the old methods of chemical and physical tests.

Another important feature of the magnetic-mechanical test is that it shows quite clearly differences in the mechanical properties of steel, where the other methods of test fail to indicate them, and where practice has shown that such differences do exist. Two pieces of steel may have the same Brinell hardness, for instance, and still possess entirely different mechanical

characteristics. The magnetic-mechanical test is not restricted to work in the laboratory. Products like tools, saw blades, drills, ball bearing races, milling cutters, etc., can be subjected to routine tests in the plant, and in case some of these show distinct differences in magnetic properties against the average run, it is safe to assume that something is wrong with their mechanical properties, so that "seconds" can be easily separated and the quality of tools of established trademark can be at all times fully maintained. Among the many other steel products which readily lend themselves to this method of test are files, knives, drill rods, wires and wire ropes, springs, steel balls, plates, sheets, strips, etc. Fig. 33 shows a typical Fahy permeameter for magnetic-mechanical analysis of wires, wire ropes, and rods, and this apparatus is of considerable importance at this time for testing the wires used in airplane construction. Not a "specimen" of the material is subjected to the test, but the wires and cables actually entering into the construction of the planes. The slightest lack of homogeneity or otherwise invisible defects in the stranded wires are clearly shown up and danger is thus prevented. Similar tests can be applied to elevator and hoisting cables; in such cases the apparatus is mounted permanently and defects can be detected before accidents happen. The main reason why this important method has not found considerably wider practical application heretofore was the difficulty in the operation of the instruments which had been available for conducting magnetic tests.

Effect of Different Elements on Steel. — The different elements that enter into steel — carbon, manganese, phosphorus, sulphur, and silicon — all have a decided influence upon the quality of the steel. The methods used in the production of special alloy steels also lend peculiar characteristics to the steel. In the following paragraphs, the effects of those elements that may be present in all classes of steel will be dealt with, while the effect of nickel, chromium, vanadium, tungsten, titanium, etc., will be dealt with in subsequent chapters covering alloy and tool steels.

Effect of Carbon on Steel. — The general influence of carbon on steel is to increase the tenacity, hardness, and stiffness. The

tensile strength is increased from 600 to 800 pounds per square inch for each additional point of carbon, while the ductility is decreased about 0.5 per cent for each point. Steel having a carbon content of 0.20 per cent begins to show an appreciable hardening effect when cooled quickly. In the normal or annealed state, steel will begin to show evidence of brittleness when the carbon has reached approximately 0.70 per cent.
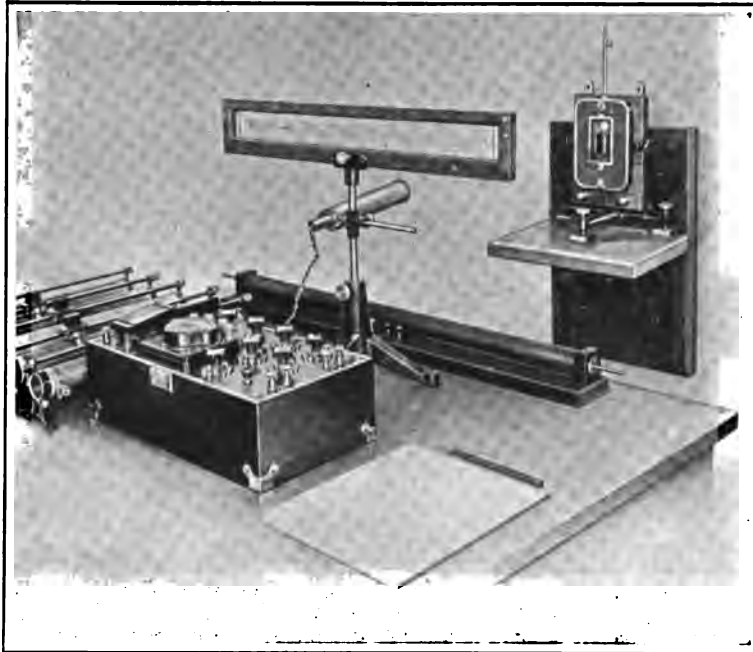

Fig. 33. Apparatus for Investigation of Mechanical Properties of Iron and Steel Wires, Ropes, Rods, etc., by Determination of their Correlated Magnetic Characteristics

High-grade razor steel contains about 1.25 per cent of carbon; spring steel, 1 per cent; steel rails, from 0.50 to 0.75 per cent; and soft steel boiler plate may have as little as 0.10 per cent of carbon, or even less. Steel which is very low in carbon can easily be welded, but it cannot be hardened; when the carbon content is above 0.33 per cent, welding is more difficult and can only be done by the use of borax or some other flux, or by the electric or thermit method. Steel with carbon above 0.75 per cent can

be hardened, that is, when heated to red heat and then quenched in water or other liquid, it becomes very hard and can be used for tools of various kinds, such as saws, files, drills, chisels, cutlery, etc.   The manufacture of steel, therefore, depends principally upon obtaining the right proportion of carbon.

Effect of Manganese on Steel. — Manganese increases the tensile strength of steel by about 100 pounds per square inch for each additional point, while the ductility is probably somewhat decreased, but this effect is not so marked.   For medium steel, the manganese content is usually from 0.40 to 0.60 per cent. More or less manganese may be specified for special purposes, depending upon the amount of other impurities, although for steel to be heat-treated, especially in the presence of high carbon, high manganese is objectionable.   Steel with more than 1 per cent of manganese should be avoided, because of its increased hardness and tendency to brittleness, except when manganese enters into special steel as an alloying element; in the so-called "manganese steel" the manganese varies from 7 to 12 per cent.

Effect of Phosphorus on Steel. — Phosphorus increases the strength of steel, but owing to its tendency to render the metal cold-short, or brittle, it should be considered as an impurity and avoided as much as possible.   The lower the phosphorus content the better, except possibly in spring steel, where a minimum limit is frequently specified.

The specifications for steel intended for constructional purposes usually limit the phosphorus content to from 0.04 to 0.08 per cent, depending upon the class of steel and the process of manufacture.   (See specifications under following paragraph on "Effect of Sulphur on Steel.")   When a structure is subjected to static loading only, Bessemer steel may be acceptable with the phosphorus content limited to 0.08 per cent.   According to some authorities, a higher phosphorus content than is commonly specified will not cause the injurious effects frequently attributed to this element.   According to a paper presented before the Iron and Steel Institute in London, by Dr. J. E. Stead, on the "Influence of Some Elements on the Mechanical Properties of Steel," there is no reliable record showing that

sound steel rails containing from 0.07 to 0.09 per cent of phosphorus break on the track more frequently than those containing less phosphorus. It is also claimed that phosphoretic rails resist wear better than the same rails having less of this element; in fact, when iron rails were in use, it was the practice to have the iron very rich in phosphorus in the heads of the rails in order to make them wear better. When steel was introduced, carbon replaced phosphorus.

Phosphorus tends to give steel clean bright surfaces and increases the elastic limit and tenacity. From 0.13 to 0.20 per cent is required to give steel good machining properties. When phosphorus is alloyed with iron, the metal is less liable to corrode and it is useful in this respect. Phosphorus is also introduced into tin-plate bars, as it prevents the sheets from sticking together during rolling. Phosphorus, therefore, is not invariably an injurious element, although the use of high phosphorus steels in general is not advocated.

Effect of Sulphur on Steel. — Sulphur is generally classified as an injurious element in steel, although recent experiments and tests indicate that the effect of sulphur has not been fully understood and that many specifications require much smaller amounts of both phosphorus and sulphur than is necessary. In the paper by Dr. J. E. Stead, previously referred to, a number of important points regarding the influence of sulphur were mentioned. To begin with, the effect of sulphur alone on steel without manganese is to produce red shortness, and injurious effects attributed to sulphur in the early days of steel-making were doubtless due to the difficulty of getting a sufficient quantity of manganese into the steel without unduly increasing the carbon content, because at that time the only spiegeleisen available contained about 4.5 per cent of carbon and from 7 to 9 per cent of manganese. When spiegeleisen was produced containing 20 per cent of manganese, there was little or no red shortness, and when the manganese was still further increased, sulphur ceased to be the injurious element it had been previously.

Manganese counteracts the effect of sulphur, but steel rails and other parts of exceptional quality are often rejected because

the sulphur content exceeds arbitrary limits even when all mechanical tests have proved that the material is satisfactory. In an exhaustive series of tests, steel containing 0.15 per cent of sulphur gave better impact tests than any of the other steels used, and it proved much superior to a similar steel containing only 0.015 per cent of sulphur. Sulphurous steel, however, is weaker when tested transversely. For example, ship and boiler plates high in sulphur are weaker transversely than in the direction in which they were most extended by rolling. When the steel is to be stressed transversely to the rolling direction, the sulphur should be low, but if it is stressed in line with the rolling direction, sulphur is not considered detrimental. Steel high in sulphur resembles wrought iron and is more or less fibrous. In fact, sulphur is deliberately introduced into a class of steel known as "free-cutting fibrous steel" which contains about 0.15 per cent of sulphur. A moderate amount of sulphur tends to produce smooth machine surfaces as compared with a low sulphur steel which is relatively difficult to machine.   •

While some of the preceding references to sulphur might be regarded as favorable to a relatively high sulphur content, the author of the paper previously mentioned emphasizes the fact that, in general, the less sulphur and phosphorus, the better. The point is that for certain purposes these elements may confer desirable properties upon steel. The more sulphur steel contains, other conditions being constant, the more rapidly it is attacked by acid solvents. It has also been alleged that high sulphur is conducive to increased corrosion. Sulphur has a tendency to render steel red short, so that it is to be avoided in any steel that must be forged or otherwise worked hot. Hot shortness is also liable to cause trouble, especially in steel that is to be casehardened or heat-treated.

The Manufacturers Standards Specifications for structural steel, as revised April, 1914, includes three classes of structural steels designated as Class A, which is used for railway bridges and ships; Class B, for buildings, highway bridges, and similar structures; and Class C, for structural rivets. Classes A and C must be made by the open-hearth process, whereas Class B

may be made either by the open-hearth or Bessemer process.

Class A: — The maximum phosphorus content, when made by the basic open-hearth process, is 0.04 per cent; when made by the acid open-hearth process, 0.06 per cent. The maximum sulphur content is 0.05 per cent.

Class B: — The maximum phosphorus content, when made by the basic open-hearth process, is 0.06 per cent; when made by the acid open-hearth process, 0.08 per cent; and when made by the Bessemer process, 0.10 per cent. The sulphur content is not specified.

Class C: — The maximum phosphorus content, when made by either the acid or the basic open-hearth process, is 0.04 per cent. The maximum sulphur content is 0.045 per cent.

Effect of Silicon on Steel. — Silicon is generally supposed to render steel cold-short, but there is little evidence that silicon in a small quantity will do this. In ordinary steel, the silicon is usually limited to 0.20 per cent, but there are special silicon steels where the silicon tends to increase the tensile strength but decreases the elongation and reduction of area.

Effect of Copper on Steel. — It has been found that steel containing from 0.30 to 0.35 per cent of carbon, from 0.25 to 0.35 per cent of silicon, from 1.00 to 1.20 per cent of manganese, from 1.50 to 1.80 per cent of nickel, from 0.50 to 0.80 per cent of copper, and not over 0.05 per cent of phosphorus and sulphur will have the same properties as a 3-per-cent nickel steel. When properly heat-treated, it will have a tensile strength of 95,000 pounds per square inch, an elastic limit of 65,000 pounds, an elongation of 18 per cent, and a reduction of area of 30 per cent. If the steel also contains 0.50 per cent of chromium, its physical properties will be the same as a steel containing 1 per cent of chromium and 3 per cent of nickel. Its tensile strength will then be 140,000 pounds per square inch; its elastic limit, 110,000 pounds per square inch; its elongation, 17 per cent; and its reduction of area, 44 per cent. The addition of copper diminishes the brittleness of the steel at low temperatures.

Influence of Various Metals on Corrosiveness of Steel. — Silicon in steel increases greatly its tendency to corrode; 0.3

per cent of silicon will make iron rust 20 per cent more rapidly than would ordinary steel free from silicon. On the other hand, alloying steel with nickel or copper gives it increased resistance to corrosion; 0.2 per cent of copper in steel produces a material which is attacked by acids at one-tenth the rate of ordinary steel. The corrosion in the atmosphere is only one-third that of steel free from copper. An increase of copper above 0.2 per cent does not add to the corrosion-resisting qualities of the steel. These results have been obtained not merely by laboratory experiments but in practice. Roofs have been covered in and around Pittsburg with ordinary sheet steel and also with a sheet steel containing 0.2 per cent of copper. The copper-alloy roofs were in good condition when the ordinary sheet-iron roofs were completely corroded.

Necessity of Various Elements in Steel. — Carbon and manganese add most to the strength of steel in proportion to what they detract from the ductility, and are, therefore, the most desirable elements to have present. It is, however, neither desirable nor possible to have a steel free from all elements but these. The other elements are present as impurities in the iron ore and the fuel, and while it is generally possible to reduce them to a very small amount, it is impossible to eliminate them entirely. Then, too, the presence of some of these impurities is absolutely necessary in order that the steel shall be sound and readily worked. Silicon, in particular, has a highly beneficial effect in making the steel more sound and homogeneous.

Steel having a very small percentage of impurities has two faults: 1. When the liquid mass is cast into an ingot, the impurities tend to gather into one place, thus forming hard brittle spots in a steel that is otherwise too soft and weak. This trouble is termed " segregation," and is obviated by a sufficient proportion of impurities, the most efficient in overcoming it being silicon. 2. Gas is present in the cooling mass in the form of bubbles, which form vacant spaces in the ingot and when flattened out, in working, become flaws in the finished piece. The remedy for this fault, also, is a larger proportion of impurities, and especially silicon.

CHAPTER VI

CRUCIBLE STEEL

THE crucible process was formerly used for making all the high-grade tool steel used for metal-cutting tools and, consequently, the terms "tool steel" and "crucible steel" are often used interchangeably, but at the present time the electric furnace is used extensively for producing tool steel which should not be classified as crucible steel. Few mechanical processes have, during the general progress of engineering, undergone so little change as the methods employed in the making of tool steel by the crucible process. With the exception of a more direct method for introducing the carbon into the steel, it may be said that, in general, the same methods are still used as were employed a century ago, although improved methods for heating the furnaces and for handling and working the steel at the various stages of manufacture have been introduced during the course of mechanical development. Briefly described, the method of producing crucible or tool steel consists in using wrought iron containing as small a percentage of phosphorus and sulphur as possible, and adding carbon to it. Two methods have been in use for accomplishing this result, the older one being the so-called " cementation " process, the newer being the regular crucible process.

Cementation Process. — The cementation process is similar, in principle, to the ordinary casehardening process for giving parts made of low-carbon machine steel a hard high-carbon surface. In the cementation process, wrought-iron bars are packed in long air-tight cast-iron retorts containing enough pulverized charcoal so that each bar will be well bedded in it. When the retorts are thus filled, they are placed in a furnace, called the " cementation furnace," where they are heated to a red heat, at which temperature they are kept for several days — anywhere

from six to ten days — after which they are permitted to cool down slowly. When the bars are heated, they absorb carbon from the charcoal in which they are packed. The amount absorbed depends upon the length of time they are exposed to the high temperature. The absorption of carbon may amount to as much as 1½ per cent. The product obtained by this process is known as " blister steel," as the surface of the bars is covered with small scales or blisters. When cool, the blister bars are hammered into longer bars, which are then cut, piled, heated, welded, and again hammered out into bars. The product so obtained is known as " single shear steel." When this is again cut, piled, heated, welded, and hammered out into bars, the product is known as " double shear steel." This method of producing tool steel does not render as uniform a material as the regular crucible process, as the amount of carbon in the bar varies; it is greatest at the surface and least near the center.

Crucible Process. — In order to obtain a more uniform steel than that produced by the cementation process, Benjamin Huntsman, a Sheffield watchmaker, about 1740, devised a process of melting blister bars in clay pots or crucibles. This method is still used for the production of some Sheffield tool steel; blister bars made from Swedish charcoal iron of uniform carbon content being used for the raw material. The American method of producing crucible steel is similar to this, except that, instead of using blister bars, wrought iron is melted directly in crucibles without any cementation process preceding this melting, and the carbon is added directly in the crucible in the form of powdered charcoal. The wrought iron is cut up into small pieces before being put into the crucible. The charge is melted and is permitted to remain in the molten state for some time before being poured into molds. While in the molten state, the iron absorbs carbon much more quickly than when only red hot, as in the cementation process. When the carbon is added directly in the crucible, it is also possible to more accurately determine the carbon content of the final product, and, for this reason, the crucible process, as employed in America, is held to be superior to the crucible process using blister steel. Steel containing the

required amount of carbon is obtained in a few hours, while, by the original Huntsman process, a period of nearly two weeks is required.

There are some variations in the raw material used for crucible steel. In Sweden, wrought iron and pig iron are sometimes melted together, and also pig iron and iron ore, but these methods have not been used to any extent in the United States. American makers, however, have used Bessemer and open-hearth soft steel instead of wrought iron, for a number of years, but this process gives an inferior product. The best material for the making of crucible steel is generally conceded to be Swedish (Dannemora) wrought iron having a carbon content of from 0.10 to 0.20 per cent. This iron comes in flat bars, $\frac{1}{2}$ by 2 inches, and is cut up into small pieces about 1 inch wide. Swedish wrought iron is used in preference to the domestic material, because it produces a superior tool steel. It is possible to obtain domestic wrought iron having by chemical analysis practically the same composition as the Dannemora iron, but the tool steel made from it will not be of as good a quality. Some metallurgists claim that the reason for this is that the Swedish iron ore originally contains a small amount of vanadium, which, while it is eliminated during the process through which wrought iron is produced, so that it is not present in the wrought iron itself, nevertheless has an influence upon the quantity of wrought iron, because of its effect in making the iron.

The reasons generally given for the superiority of crucible steel are that a metal almost free from sulphur and phosphorus is used as the raw material; the iron, when in the molten condition, is protected from the oxidizing gases of the furnace by being kept in a covered crucible; and the carbon content can be very accurately controlled.

Crucibles Used. — The crucibles used in the crucible process for making tool steel are either made from clay or graphite, and hold anywhere from 60 to 125 pounds. Generally, the height of the crucible is about 20 inches, and its diameter, about 12 inches at the central or largest part. When placed in the furnace, the crucible is provided with a fireclay cover. A crucible

of the dimensions mentioned will have a capacity of from 75 to 8c pounds of iron.

Clay Crucibles. — Clay crucibles are generally used in Europe, while graphite crucibles are preferred by many steel-makers in America; while their first cost is greater than that of clay crucibles, they are stronger and last longer. There are, however, several American steel-makers who prefer clay crucibles, especially in the making of high-grade tool steel, because, when a clay crucible is used, there is no possibility for any extraneous matter mixing with the charge, and the carbon content can be very closely predetermined. When a graphite crucible is used, small particles of graphite will flake off on the inside of the crucible, and these particles will mix with the charge. It is claimed that they will not, however, enter into a chemical composition with the steel, but will merely mix with it mechanically, so that there will be small particles of graphite imbedded in the steel, thus producing small holes and flaws in the finished material. The only disadvantage of the clay crucible is that it is easily broken when cold, and is also more likely to break in the furnace, nor will it last as long as graphite crucibles. The latter, therefore, are considered cheaper in the long run.

Making Clay Crucibles. — Clay crucibles are made from a mixture of several kinds of clay. The best quality, previous to the war, was made by mixtures of imported and domestic clays, in certain proportions. The essential qualities of the mixture are that it must be strong, plastic, and refractory, and that it should not contain any oxide of iron, alkalies, or alkaline earths. In making clay crucibles, a form is used to give it the outside shape, and a revolving former is employed to shape the inside. When the crucible has thus been formed, it is permitted to dry at ordinary room temperature, after which it is put in an annealing furnace, where it is slowly heated to a high temperature. Clay crucibles must be taken directly from the annealing furnace while hot, charged with iron and charcoal, and put into the melting furnace, after which the crucible must not be allowed to cool off until its usefulness is past. The heat of the crucible and charge while in the furnace is from 2500 to 2800 degrees F.

Graphite Crucibles. — Graphite crucibles are made from a mixture containing nearly equal amounts of graphite and clay, and a small amount of sand. The graphite must be well ground or the crucible may become porous; still, if ground too fine, the walls of the crucible will be so dense that the conduction of heat through them will be slow; besides they will not expand or contract quickly and, therefore, will have a tendency to crack. The sand used is an ordinary fire or silica sand that contains from 95 to 99 per cent of silica with small amounts of alumina, alkaline earths, or combined water. Oxide of iron and alkalies lower the fusion point, if present except in very small amounts.

After the ingredients are mixed into a thoroughly homogeneous mass, the mixture is ready for molding; at this time it contains about 22 per cent of water. Molding was formerly done by hand, but now it is done almost entirely by machines. In hand molding, a form is used to give the outside shape, and a revolving former is used to shape the inside. The crucibles are first dried at ordinary room temperature, and are then placed in the annealing furnace where they are slowly heated to a temperature of from 1400 to 1500 degrees F.; this annealing is done in some type of pottery kiln. If coal is used as a fuel, the sulphur content must be low, or the crucible will be injured by absorbing too much of the sulphur. When made, graphite crucibles should be stored in a dry and, if possible, warm place, and should be dried out on a furnace top for a week or two before being used. New pots should be heated by being placed around the melting holes before they are charged. Clay pots must not be allowed to cool off at any time.

Charging the Crucibles. — In England, the clay crucibles are placed in the furnace and then charged, a sheet-iron funnel being used for this work. The American practice, when these crucibles are used, is to heat the crucibles in the furnace, remove them for the charging, and quickly replace them in the furnace. Graphite crucibles are charged when cold, after they have been tested for thickness and cracks. In some mills, the larger pieces of iron and the charcoal are placed at the bottom and the smaller and more closely fitting pieces are placed at the top. In other

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mills, one-half of the charge is placed in the crucible, then a bag
containing the charcoal, then the rest of the iron.   Fig. 1 shows
crucible, a charge of Swedish iron, and a bag of charcoal.   The
crucible containing the charge is covered with a clay top and put
into the furnace.   When high-speed steel is made, other ingredi-
ents, such as chromium, tungsten, molybdenum, etc., are placed
in the crucible together with the charcoal and iron.

Determination of the Carbon Content of Steel. — The carbon
content in the steel is determined by the amount of charcoal in
the charge.   It is not possible, however, to calculate directly

Fig. 1.   Charge for Making Crucible Steel, consisting of Swedish
Iron, a Bag of Charcoal, and the Clay Crucible in which the
Charge is melted

the proportions of charcoal necessary for a certain weight of iron
to produce a given percentage, as some carbon is contained in the
wrought iron.   Some of the charcoal is also lost in the slag.
The common method of determining the amount of charcoal re-
quired is to consider that each ounce of charcoal will give about
0.07 per cent of carbon to the steel; or, as the steel-maker ex-
presses it, one ounce of charcoal gives seven "points" of carbon.
This proportion is approximately correct for ordinary carbon
contents, but, when steel of a very high carbon content is re-
quired, it is necessary to add charcoal in a greater proportion,

partly because the original amount of carbon in the wrought iron is of relatively less importance, and partly because more of the carbon is lost or wasted.

Melting Furnaces. — Crucible furnaces may be heated by coal or coke, oil or gas. When solid fuel is used, the crucibles are practically buried in the fuel beds, but when liquid or gaseous fuels are used, the crucibles are arranged so that the burning gases pass around them.

A *coal hole* is the name of a furnace that burns a solid fuel. This furnace is formed by making, in a pit in the work-room floor, a combustion chamber which is connected to the chimney by a flue and has a working space in front of it for the men attending to the fires. The top of this working space is covered by bars which admit light and air, and also allow any steel that may be spilled during pouring to fall into the pit, instead of running over the floor. The top of the combustion chamber is protected by a cover. These pits are generally lined up along one side of the room. The melting hole is large enough to hold from four to six crucibles, and is about four feet deep. The forced blast is introduced into the ash-pit, and a short flue connects the melting hole with the main flue. The melting hole cover is generally in three sections to facilitate handling.

In operation, a small fire is started on the grate bars and is built up until the bed of glowing coals is about a foot thick. Then, from six inches to a foot of coal is dumped on the fire and the crucibles placed upon it, after which coal is carefully packed around and on top of the pots, and air is admitted through a pipe. The fire should be blown gently at first, especially when new crucibles are used, because, if the crucibles are heated too rapidly, they will spall or crack. After about two hours, the crucibles must be raised and more fuel forced under and around them until the fuel bed is level with the top of the crucibles, when the cover is placed on the combustion chamber and the fire is again forced. In from one to three hours more, the steel is ready to pour.

In English mills, coke is generally used as the fuel, but in the United States anthracite is used, although sometimes coke is

mixed with it. In the latter case, when the crucibles are reset
in the fuel, anthracite is used almost entirely, because coke burns
too rapidly. When coke is used, the crucibles must be raised
and the fuel bed fixed three or more times during a heat.

The advantages of this type of furnace are its low first cost and
its suitability for intermittent operation; the chief disadvantages
are the high cost of the steel due to the low tonnage produced,
the heavy wear on the crucibles, the high fuel consumption, and
the high cost of labor.

Oil-burning Furnaces. — In localities where oil is cheap, oil-
burning furnaces are sometimes used. In some of these the oil
is burned in a chamber alongside of the melting hole, and the
hot gases pass around the crucibles on their way to the chimney.
In others, steam or air is used to atomize the oil, which is blown
into the melting chamber; the oil is ignited as soon as it is vapor-
ized. While these furnaces cost more to install than a coal hole,
they are cheaper to work, because of the reduced labor cost, as
no coal or ashes need be handled. The melting also is more
rapid, giving a larger output.

Gas-fired Regenerative Furnace. — Most crucible furnaces
are of the regenerative type. They are heated by gas which,
with the air necessary for its combustion, passes into the furnace
alternately from either the one side or the other. When the gas
enters on one side, the exhaust gases pass out through a checker-
brickwork on the other side. The exhaust gases being of a
very high temperature heat this checker-brickwork to a red heat.
At this time, the entering gas is automatically shut off from the
one side, and gas is now admitted from the opposite side that
has been heated by the exhaust gases. This gas then, passing
through the heated checker-brickwork, is thoroughly pre-
heated, so that when combustion takes place, a much higher
degree of heat is obtained. The combustion gases from this
side now heat the checker-brickwork on the other side, and the
process of preheating the gas as it enters alternately from the
two sides of the furnace is thus automatically taken care of.

As in the other types, this furnace is usually placed below the
working-room floor, so that the crucibles are easily handled.

Air is admitted through the outside chamber A, Fig. 2, and gas through the inner chamber B. As they mix, they ignite and pass into the melting chamber, and then through chambers D and E to the chimney. When the brickwork in chambers D and E is heated to the desired temperature, the valves are turned, and the gas and air are supplied to the furnace through chambers D and E, while the waste gases pass off through chambers A and B. This reversal of the flow of the gas and air and the waste gases is made at regular intervals. It is immaterial whether the gas chambers are on the inside of the air chambers,
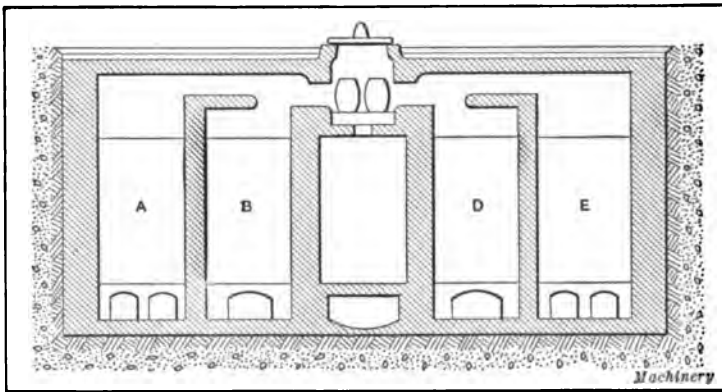
Fig. 2. Gas-fired Regenerative Crucible Furnace

as here shown, or on the outside, so long as the air is arranged to enter above the gas. This furnace is the most costly to install, but is the cheapest to operate, and may be used with producer or natural gas. When natural gas is used, only the air is preheated, so that both sets of checkerwork chambers are used for air or only one set is provided. The bottom of the melting chamber is generally provided with a bed of coke breeze, to prevent the crucibles from sticking to the brick lining of the melting chamber.

The *Krupp regenerative furnace*, which is used mostly in Germany, is built above the floor and has a closed top. The crucibles are put into and drawn from it through openings in the side. This furnace is not extensively used in the United States. One objection to it is that the condition of the steel cannot be known unless one goes to the top of the furnace and looks through small

holes in the roof. Another objection is that any steel that may be spilled is supposed to run to the back of the furnace and then to flow out through a tap hole. The gases, however, soon change this iron into a carbonless iron that will not run through the tap hole and which must be pried off the bottom of the hearth, when it frequently takes part of the bottom of the hearth with it.

Operating the Crucible Furnace. — The charging floor, or the floor on which the men work who insert the crucibles in, and remove them from, the furnace, is level with the top of the furnace in all the ordinary American and British types. Firebrick covers are kept over the openings of the furnace at all times except when a crucible is being put in place or removed. Regenerative furnaces are always kept running continuously day and night, as they would crack and be destroyed by the severe internal stresses due to sudden cooling, if the fire were permitted to go out. The life of a regenerative furnace is usually from six months to a year, after which time it must be rebuilt.

The crucibles are placed into, and lifted out of, the furnace by means of large tongs, the men doing the work standing partly over the furnace while removing the crucible. When it is thought that a charge in the crucible is melted, which requires anywhere from two to five hours, the melter slides the lid from each pot in succession, in order to examine the condition of the steel. When first melted, the steel boils quite freely, but as the metal is held at that temperature for some time, the boiling gradually subsides. This holding of the metal at a high temperature until no more gas is evolved is known as " killing" or " dead melting," and usually takes from 20 minutes to an hour. In order to test the steel, the melter thrusts a light iron rod into the crucible with which he stirs the metal. If the metal is " cold," it is sluggish and pasty, and adheres to the rod when it is withdrawn. When thoroughly molten, or " hot," very little or no steel adheres to the rod, which may even be melted off at the end. In some of the mills, when the steel is " hot" and " quiet," the melter throws envelopes containing ferrosilicon and ferromanganese into the crucibles, replacing the lids of the crucibles and the covers of the furnace. In a few minutes, the covers are

removed and the crucibles drawn from the furnace and poured. In other mills, the crucibles are removed from the furnace as soon as the metal is in condition for pouring, and, after a crucible has been removed from the furnace, the slag collecting on the surface of the metal is first removed by a long iron bar, and then a small amount of ferromanganese is put into the crucible. Whether the ferromanganese is put into the crucible before or after it is removed from the furnace appears to be immaterial, inasmuch as the object of introducing this ingredient is merely to oxidize the metal while it is being poured, in order to insure freedom from blow-holes or flaws in the ingots. Other metals, such as titanium and vanadium, are frequently added in small amounts as final deoxidizers. Sometimes aluminum is thrown into the crucible, to make the metal set quietly in the mold, but, as a rule, this is not required, if the steel has been properly melted.

Ingot Molds. — The ingot molds are made in halves. They are generally made from cast iron, and their inside dimensions vary. Often they are about four inches square by three feet long. The two parts of the mold are held together by rings and wedges, one ring at the top and one at the bottom, the molds being stood on end while pouring the hot metal into them. It is essential that the finish on the inside of these molds is smooth. If the inside is not smooth, the ingot will have a rough surface, which may result in difficulties in the finished bar. The joints must also be tight, so that the hot metal cannot work through them and form a fin on the ingot. This fin would have to be removed, which would increase the cost of manufacture. If it were not removed, it would be hammered and rolled into the steel and cause imperfections. In order to prevent the steel from sticking to the molds, the latter are "smoked" by burning rosin or some other heavy, greasy, and smoke-making material underneath them. This leaves a thick black coat of smoke or soot on the face of the molds. The molds should also be warmed before they are used.

Pouring or Teeming. — The pouring or teeming is an important part of the process. It is necessary to have a steady stream of metal enter the mold. If it is stopped and started again,

there will be an imperfection in the ingot, and a bar hammered and rolled from it will not be homogeneous.   In fact, the ingot, when hammered, is likely to break at the point where the interruption of the stream occurred.   The stream of hot metal should not be permitted to strike the side of the mold, because, in that case, it is likely to cut the mold and produce a rough ingot. Furthermore, the mold will be destroyed in a few heats.   The teeming, therefore, requires considerable practice.   Sometimes the steel is not poured directly from the crucibles, but is first

Fig. 3.   Pouring the Molten Steel into Molds to form Ingots of Crucible Steel

poured into ladles, and then into the molds.   When a ladle is used, the pouring is easier, and this method is considered, by many, the better procedure, especially when uniform ingots are required, as the metal from a number of crucibles may be poured into one large ladle; hence a more homogeneous mixture is obtained.   Fig. 3 illustrates how the molten steel is poured into the vertical molds.

When clay crucibles are used, as soon as the metal has been poured, the crucible, which is not permitted to cool off because it would be destroyed by cracking, is put back into the furnace to be heated up again before recharging.   In some cases, when

it has not cooled off too much during the pouring, it will be immediately recharged without reheating. When reheated, however, it is removed from the furnace after a few minutes, and the charge put into it as already described. It is then immediately put back into the furnace where it is permitted to remain from four to six hours, when it is again removed, and the metal poured, and the same process repeated. When a furnace is in operation day and night, about five heats are generally obtained in the course of twenty-four hours. A clay crucible will only last for about from four to six heats.

Piping. — One of the greatest difficulties in making crucible steel ingots is due to "piping"; that is, the formation of a spongy mass or even a hole at the center of the ingot. Piping is caused by the side of the ingot cooling faster than the central part. As the metal in the ingot cools and solidifies toward the sides, the still molten metal at the center separates and a "pipe" forms. There is a greater tendency for a pipe to form at the top of the ingot than farther down, because a tendency for a pipe to form in the lower part is offset by the metal from the upper part of the ingot filling the space formed. The most general method for avoiding piping in crucible steel is by the use of so-called "hot tops." A "hot top" is a brick made of fireclay with a hole through it, the size of the brick and the hole depending upon the size of the ingot. The method of using a hot top is described by George H. Heilson, in an address before the Engineering Society of Western Pennsylvania, as follows: When the mold has been almost filled, the hot top is placed on top of the hot steel in the mold and the hole filled with the melted steel. This plug, as it may be called, settles into the pipe as it develops, and also has a tendency to keep the top of the ingot hot and thus lessen the pipe. The hot top, however, does not prevent the formation of small cavities below the main portion of the pipe. It should be remembered that the hot top brick must be heated to as high a temperature as it will stand before being placed on the ingot. If this is not done, the cold brick will chill the steel and destroy the usefulness of the hot top. When the ingots are cold, the top is broken off so that a clean

fracture is obtained, which is used for judging the carbon content.

Welding Process. — After the ingot has been poured in the mold, it is permitted to cool off, after which it is removed from the mold. The next operation performed is the heating of the ingots in a furnace to a welding or white heat, after which they are put through what is termed the "welding" process. This consists in placing the white-hot ingot under the steam hammer and lightly tapping it with gentle blows on the surface so as to close up or weld all minute cracks or flaws that may be present on the outside of the ingot. This insures a homogeneous structure and freedom from flaws and cracks in the finished material. The welding process is not always carried out, as it is considered unnecessary when ingots are poured in very smooth molds.

Hammering the Bars to Size. — The ingot may be reduced to its required size and shape either by hammering or by rolling. Those bars that are hammered to the required size are either permitted to cool down, after having been welded, and are then reheated to a red heat, or they may be immediately taken from the steam hammer, where the welding was done, and placed under the steam hammer where they are to be hammered to size. The hammering adds to the firmness and quality of the steel, and insures homogeneity of the material. In order to insure the correct size being obtained, tools similar to those employed by regular blacksmiths are used as stops and gages. A square block provided with a long shank, called a "peg," is placed on the anvil of the hammer and acts as a stop. (Several of these blocks are shown in Fig. 4.) This block has a thickness equal to the required thickness or diameter of the bar. When the steam hammer has hammered down the bar to this size, it will strike this block, and is thus prevented from making the bar under size. After the bar has been thus hammered down to a given size, by using the pegs as stops, it is gaged by sheet-iron snap gages at various places, in order to ascertain that it is of the correct size uniformly along its whole length. For round bars, swages similar to those used by the ordinary blacksmith are employed to obtain a round and smooth surface. When the

bars have been hammered down to the correct size, they are annealed in order that they may be soft enough for working. The annealing furnace generally contains a number of long large pipes; they may be regular cast-iron water or gas pipes. The

Fig. 4. A Collection of Tools used when Handling Crucible
Steel Ingots and Hammering them to Size

bars are placed in these pipes and the ends of the pipes are sealed with fireclay. After this, the front of the furnace is closed by a cover and it is heated for about twenty-four hours. Then the fire is deadened, and the bars are permitted to cool slowly for about two days; they are then ready for the market.

Rolling the Bars. — Small sizes of square and round stock are generally not hammered into shape, but are rolled to the required size. The ingot is first heated to a high heat and is then placed between the first set of rolls, after which it passes between the rolls from one side to the other, becoming smaller in cross-section and of greater length at each successive pass. When the

"Carbon-temper" of Steel
(JOSEPH T. RYERSON & SON)

Temper Number	Per Cent Carbon	Tools for which Steel is Adapted
7	0.65 to 0.75	Blacksmith's hammers, table knives, dies for drop hammers, large hot forgings, flatters, fullers, track chisels, and tools.
8	0.75 to 0.85	Large shear knives, punches, chisels, hammers, boilers, boiler-makers' tools, lathe centers, etc.
9 .	0.85 to 0.95	Punches and dies, hand chisels, mining tools, shear blades, etc.
10	0.95 to 1.05	Drills, large milling cutters, axes, taps, reamers, bolt header dies, and similar tools.
11	1.05 to 1.15	Granite chisels, milling cutters, taps, reamers, mill picks, threading dies, cups, cones, etc.
12	1.15 to 1.25	Milling cutters, small taps, threading dies, twist drills, forming and boring tools, mandrels, razors.
13	1.25 to 1.35	Inserted milling cutter teeth, lathe, planer and slotter tools and tools requiring great hardness.
14	1.35 to 1.45	Cutting disks, granite lathe tools, paper knives, engravers' tools, roll corrugating and chilled roll turning tools.
15	1.45 to 1.55	Steel for turning chilled rolls, etc., requiring great hardness.

ingots are to be rolled down to very small sizes, the work is done in two stages, owing to the great length of the bar when it has been rolled down to a comparatively small size. In such cases, the bar, after having been rolled down to a certain size is cut up under shears into shorter pieces of equal length, immediately after coming from the rolls. These pieces are then reheated in

the furnace and are again rolled to produce smaller sizes.

Crucible steel ingots should be handled with great care in heating for rolling and hammering. The flame of the heating furnace must not be strongly oxidizing, and the ingots should be brought to the forging or rolling heat very slowly. The reduction in rolling must be small compared with the practice followed for commercial Bessemer or open-hearth steels. Crucible steel cannot be handled in the same way. As an illustration, in reducing a 3-inch square billet of open-hearth steel to $\frac{1}{2}$ inch round, there would be, perhaps, 14 passes through a mill driven at a high speed. With crucible steel, there would be 21 passes through a mill driven at a much slower speed.

Grades of Crucible Steel. — Crucible steel is graded according to its " temper," the term " temper" or " carbon-temper" being used by steel-makers to indicate the amount of carbon in the steel. " One" temper is generally taken to mean 0.10 per cent of carbon. This designation, however, for the percentage of carbon varies with different makers. The accompanying table gives a list of tempers and the purposes for which the various steels of given temper number are adapted, as listed by one dealer.

To assist in their grading, as the bars have been hammered to size from the ingots, they are nicked on all sides with a triangular tool at what was the upper end of the ingot. After they are cold, the end pieces are broken off. The appearance of this fracture indicates the amount of carbon in the steel, and it is claimed that a trained inspector can tell from the fracture the carbon content of the steel within 0.05 per cent.

The best all-around tool steel contains from 0.90 to 1.10 per cent of carbon, and can be adapted to a wider range of uses than any other grade. For tools, generally, it gives the highest strength together with a high degree of hardness when heat-treated. It cannot, however, be welded easily. Steels containing up to 1.50 per cent of carbon are easily burnt, and are welded only with great difficulty. They can, however, be hardened to an extreme hardness. When the carbon content is 0.75 per cent, the steel is more easy to weld, but will not become very hard when heat-treated.

CHAPTER VII

THE BESSEMER PROCESS

NOTWITHSTANDING the high cost of making steel by the crucible process, no more satisfactory method was developed until 1855. In that year, Sir Henry Bessemer patented a method of producing steel by blowing air through molten pig iron, and in this way reducing the carbon, silicon, and manganese content by burning out the greater amount of these constituents. The metal first produced by the Bessemer process, as originally applied, was a nearly carbonless iron, but the iron obtained from the early experiments produced ingots that were full of blow-holes and which could not be used commercially. For some time, therefore, the process was merely used for burning out the carbon from pig iron. The molten metal was then granulated by being poured, while in the molten state, into water, after which it was converted into steel by the crucible process. Later, however, the process was improved so that steel could be made directly in the converter by first burning out the carbon as explained, and then adding the required amount of manganese and carbon to produce a steel with a definite carbon content. This invention so reduced the cost of steel that it is doubtful if any other invention or discovery has had so large an influence on industry and manufacturing in general. Furthermore, the Bessemer process makes available for use in steel-making large deposits of iron ore that are not suitable for the crucible process. For the better grades of steel, however, the Bessemer process has been replaced largely by the open-hearth process.

Tonnage Produced by Bessemer and Open-hearth Processes. — Prior to 1908, more steel was produced in the United States by the Bessemer process than by the open-hearth process, but since that time the use of open-hearth steel has increased greatly. The following figures, which represent the gross tons produced

in the United States, indicate the relative importance of the Bessemer and open-hearth processes at different periods. In 1880, the Bessemer tonnage was 1,074,260 and the open-hearth, 100,850; in 1890, Bessemer, 3,688,870, open-hearth, 513,230; in 1900, Bessemer, 6,684,770, open-hearth, 3,398,135; in 1907, the Bessemer and open-hearth tonnages were approximately

Fig. 1. A Bessemer Converter

equal; in 1910, the Bessemer tonnage was 9,412,770, as compared with 16,504,510 for the open-hearth process. In 1916, nearly three times the tonnage was produced by the open-hearth process, the figures being for the Bessemer, 11,059,040, and for the open-hearth, 31,415,430.

Principle of the Bessemer Process. — Briefly described, the Bessemer process for making steel consists in putting molten pig iron in a large pear-shaped vessel called a *converter* (see Fig.

1), in which the carbon and other impurities are oxidized and re-
moved by blowing air up through the molten mass. The air is
unheated and has sufficient pressure to prevent the molten metal
from entering the tuyeres through which the air is blown. The
required pressure is about twenty pounds per square inch.
The molten iron is poured into the converter in quantities of
from ten to twenty tons at a time directly from the blast furnace, while the converter is in a horizontal position. Then the

Fig. 2. A Bessemer Converter Pouring

compressed air is turned on as the converter is raised to a ver-
tical position. When the carbon, silicon, and other elements
have been practically burned out, which requires less than ten
minutes, the converter is again turned to the horizontal position,
the blast is shut off, and the proper carbon content is given to the
steel to be made by recarburizing the mass of molten metal by
adding spiegeleisen or ferromanganese. These are added in
liquid form, and after these ingredients have properly been taken
up by the molten metal, the liquid steel is poured into ingot
molds, and the ingots, while still hot, are rolled into blooms,

billets, or rails, without additional reheating, except for a short period in a so-called "soaking pit." The molten metal may also be cast directly into steel castings. Fig 2 shows the metal being poured from a Bessemer converter.

There are two specific Bessemer processes in use, one known as the *acid* Bessemer process and the other as the *basic* Bessemer process. In the acid process, the converter lining is made of refractory acid materials composed principally of silica, so that the phosphorus and sulphur content in the charge of molten metal remains unreduced. The acid process is generally used in the United States, there being a sufficient supply of low phosphorus and sulphur ores to employ this process almost exclusively. Steel of a fair quality is produced by this process at low cost and with great rapidity. In the basic process, the converter is lined with burnt dolomite, and lime is added to the charge of molten metal to reduce the phosphorus and sulphur. This process is used only when so-called "Bessemer ores," low in phosphorus, are not available.

The Converter. — The converter in which the blowing operation is carried on consists of a casing of thick iron plates lined with refractory material and supported by trunnions. Air from a blast pipe is admitted through one of the trunnions, and a pinion is keyed to the other. A hydraulic ram geared to this pinion turns the converter into a horizontal position for charging and discharging, and into an upright position for blowing. In most steel-making mills, the air passes from the trunnion to a wind-box at the bottom of the converter, and then through the tuyeres into the vessel. In the steel foundry and some places making only a small quantity of steel, side-blown converters are used, but, in either case, the process is the same; the principal difference is in the amount of steel made.

In the bottom-blown converter, the wind-box is of cast-iron, and is easily removed and taken apart. The tuyeres, too, may be quickly removed from the converter, as the entire bottom is held to the vessel by hooks and links. The tuyeres are cylindrical clay bricks that extend from the plate covering the wind-box to the surface of the refractory bottom; each brick is pierced

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with a number of openings. Enough tuyeres are provided so
that the combined area of their openings is about 2.5 square
inches for each ton of charge. If large openings and a rather low
blast pressure are used, the air passes through the bath in large
bubbles. Small openings and a pressure of from 10 to 30 pounds
per square inch cause the air to be broken into spray and so
brought into more intimate contact with the metal.

Converters may have a concentric or an eccentric nose. Many
steel-makers prefer a nose that is fixed at an angle of about 30
degrees with the body; the straight- or concentric-nose vessel,
however, is generally preferred, as it is claimed that it does not
"slop" as much as the other; that is, less metal is thrown out
of the converters by the violence of the action. In either form,
the modern converters generally hold about twenty tons of
molten metal.

Converter Linings. — In American practice, the converter is
commonly lined with ganister or silica brick, which forms what
what is known as an *acid lining*. Steel made in these converters
is known as *acid steel*, and the process is then spoken of as the
acid process. This lining is about 12 inches thick and lasts from
three to five months, or for from 3000 to 5000 heats. The
bottom, however, only lasts for from 30 to 35 heats, as a rule,
owing to the intense heat at the ends of the tuyeres. It is made
of ganister rocks and clay, or by filling the spaces around the
tuyeres with large bricks set on end and tamping ganister in
the interstices with molders' rammers. The bottom may be
from 26 to 30 inches thick. As soon as it is made, it is placed
in ovens and thoroughly dried.

As the bottoms are quickly burned away, arrangements must
be made for their quick and easy renewal. In some places, the
converter is turned into a vertical position with the bottom up;
the bottom is then removed by a crane which also puts a new
one in place. As soon as this is fastened in position, the con-
verter is ready for use. · In other plants, a car is run under the
converter and raised against the bottom by a hydraulic lift. · As
soon as the bottom is unfastened from the converter, the car is
lowered and a car carrying a new bottom is run upon the lift

and raised into place. When this bottom is fastened to the converter, the lift is lowered and the converter is ready for use.

Sometimes, the lining consists of dolomite. This is known as a *basic lining*, the steel made in this converter is known as *basic steel*, and the process is termed the *basic process*. The material for this lining, after being burnt and ground, is mixed with anhydrous tar and made into bricks, which are burnt at an intense heat. These bricks are then laid with a mortar of the same material. Sometimes, however, the lining is rammed into place instead of being laid in the form of bricks, but the mixture is the same in either case. The thickness of the lining varies from 12 to 14 inches at the bottom, to from 8 to 16 inches at the nose; the bottom is from 20 to 26 inches thick. The tuyeres may be clay bricks, as in the acid converter, but quite generally are simply holes left in the bottom by ramming the clay around iron pins, which are then withdrawn. The basic converter must be larger than the acid, because of the large amount of slag and lime charged, and lasts, on the average, only for about one hundred heats.

Operation of a Bessemer Converter. — Before a converter is put into operation, its lining is brought to a red heat. It is then turned on its side and a charge of molten pig iron poured in through the mouth. The blast is turned on and the vessel is turned into a more nearly vertical position. As the violence of the blow increases, the vessel is gradually turned until it is nearly vertical.

When the converter is first turned up, all the oxygen of the blast is consumed in the oxidation of silicon and manganese so that only the nitrogen passes through the metal. The graphitic carbon is burned into the combined form, and the silicon is oxidized to silica; this combines with the oxides of iron and manganese to form slag. There issues from the mouth of the vessel, therefore, only sparks and small particles of slag and no true flame is formed. When the silicon and manganese are nearly gone, the carbon begins to burn. It is converted into carbon monoxide by the blast, and as this passes through the vessel with the nitrogen, it ignites at the mouth, producing an in-

tensely bright flame. This stage of the process, which is known as the "boil," is equivalent to the boiling stage of the puddling process. As the escape of large quantities of carbon monoxide produced by the oxidation of the carbon by the blast causes a violent agitation of the metal, the blast is now reduced. While at first it is small, the flame rapidly increases in size until it reaches its full height. When all the carbon is burned, the flame drops quite sharply, which is a sign that the process is complete.

The heat produced by the combustion of the silicon to silica and of the manganese to manganese oxide keeps the molten metal fluid until all the impurities are removed and a bath of molten iron remains. Iron is burned to a certain extent throughout the process, but when the carbon, silicon, and manganese are nearly eliminated, the oxidation of iron becomes considerable. The resulting oxide of iron is absorbed by the molten bath and is chiefly responsible for the tendency to "wildness," shown by Bessemer-blown metal.

As soon as the flame drops, the blast is shut off, the vessel is turned on its side, and a recarburizer is added to the charge. The manganese in this reduces the dissolved oxide of iron and burns the sulphur (which is in the form of iron sulphide) into manganese sulphide. A part of this floats to the surface of the bath, where the sulphur is largely volatilized as sulphur dioxide, but a part remains suspended in the metal.

Control of Conversion Process. — The Bessemer process differs from all other steel-making processes by requiring no heat from some outside source for its operation. All the heat necessary is furnished by the oxidation through the blast. In the acid process, the heat is obtained mostly by regulating the amount of silicon in the charge, about 0.25 per cent usually being sufficient. Should any blow become too hot, it is cooled by throwing into the converter scrap steel, such as the waste ends of rails and other pieces. Sometimes, as when enough scrap steel has not been thrown into the bath, steam is blown in with the blast. The dissociation of this into its component parts, oxygen and hydrogen, requires so much heat that the metal is cooled

considerably as the heat is absorbed from the metal. Many mills prefer the method of cooling by the use of steam, because it eliminates the handling of scrap and also permits the scrap to be used in the open-hearth process, which is a more economical practice.

Should the bath become too cold, the temperature may be raised by tipping the vessel forward until one or more of the tuyeres comes close to, or just above, the surface of the metal. It then oxidizes the iron which is at once absorbed by the slag; the heat of this oxidation greatly increases the temperature of the metal. Besides, the air burns some of the carbon monoxide to carbon dioxide inside of the vessel, which action also develops heat.

In the basic process, the heat is furnished by the phosphorus, so that pig iron high in this element must be used. Silicon cannot be used, because most of the heat generated by its oxide is consumed in heating the lime needed for neutralizing the resultant silica.

Effect of Raw Material on Action of Converter. — In American practice, the heats are blown in less than ten minutes, because of the small amount of impurities to be oxidized. As the manganese in the pig iron is low, the slag consists largely of silicate of iron and is quite sticky. An increase of manganese in the pig iron increases the proportion of oxide of manganese in the slag and makes it more fluid. Should it be too fluid, it may slop over the mouth of the vessel, but this may be prevented by reducing the blast pressure.

In Sweden, where small converters are quite generally used, the manganese in the pig iron frequently exceeds the silicon to such an extent that the heat of combustion of the manganese is largely substituted for that of silicon, and very watery slags are made. These slags are more severe upon linings than the more siliceous slags used in America. When these high manganese pig irons are blown, the carbon starts to burn before all the manganese is eliminated; and as the blowing is stopped when the metal contains about the amount of carbon desired in the finished steel, enough manganese is obtained to make the addition of

large amounts of spiegeleisen or ferromanganese unnecessary. The uncertainty of this method, however, has not commended its use in other countries.

Recarburizing the Metal. — Owing to the difficulty of stop ping the blow when the charge contains the exact amount of carbon and other constituents desired, the American practice is to continue the blow until a decarburized metal, known as " burnt iron," is obtained. The proper amounts of the various elements are then added to give the steel the desired strength and quality as well as to enable it to be handled in the subsequent operations of casting, rolling, forging, etc. These additions also remove from the metal such impurities as hydrogen, nitrogen, and carbon monoxide, which render the iron " wild" (that is, cause violent ebulition of the metal in the furnace, ladle, or mold) so that the ingots are full of blow-holes and unfit for use. The making of these additions is termed *recarburizing*.

The recarburizers generally used are ferromanganese, spiegeleisen, ferrosilicon, silico-spiegel, and carbide of silicon. *Ferromanganese* is an alloy of manganese, iron, and carbon; *spiegeleisen* is the same, except that it contains less than 25 per cent of manganese. *Ferrosilicon* is a very high silicon pig iron. *Silicospiegel* is a very high silicon spiegeleisen or a very high manganese ferrosilicon. These four are made in a regular iron blast furnace from properly selected ores and with special manipulation of the furnace. *Carbide of silicon* (carborundum) is an alloy of carbon and silicon produced in the electric furnace. It has been used for only a few years and has the advantage that a smaller amount is required for the same increase in silicon or carbon, and that the temperature of the steel is increased instead of lowered as is the case with the metallic alloys. This increase in temperature is due partly to heat developed by the combustion of silicon and carbon, but mainly to the fact that the decomposition of the compound releases a large amount of heat.

Sometimes metallic aluminum is used to quiet the steel, as it acts as a deoxidizer. While a given amount of silicon will combine with more oxygen than the same amount of aluminum, the latter has a much greater affinity for oxygen under the

conditions and is, therefore, the more powerful deoxidizer. Besides removing gases and making the steel quiet, it rapidly permeates the entire mass of the steel, causing the other elements to blow more uniformly, thus preventing or lessening segregation. The addition of aluminum also gives sounder ingot tops, thus lessening the loss in the scrap and slightly increasing the strength of the steel.

Methods of Recarburizing. — When only small amounts of recarburizer are being added to a large heat, the addition is thrown into the ladle as the molten metal is being poured; but when much recarburizing material is to be added, the recarburizer is melted in a small cupola and poured into the converter. In this case, a low blast is turned on for a few seconds to thoroughly mix the recarburizer with the metal, but the blast is not left on long enough to cause any loss by the blast. Aluminum and carbide of silicon are always added in the ladle; the latter produces a violent reaction if very much is used.

When the alloys do not give the necessary amount of carbon but do provide sufficient manganese, solid carbon in the form of crushed coke or anthracite is sometimes put into the ladle; this is known as the "Darby method of recarburizing." The coke or coal is placed and weighed in ordinary paper sacks that contain enough material to add 0.01 or 0.02 per cent of carbon to the steel. The amount of carbon absorbed by the steel depends upon the condition of the bath, the amount increasing with the temperature. About 44 per cent of the best anthracite used for this purpose is pure carbon; the rest is ash, etc.

Pouring the Ingots. — As soon as the blow is completed, the metal is transferred to a ladle. A layer of slag is usually poured on top of the metal to prevent the radiation of heat and to protect the metal. The converter is then turned upside down with the blast turned on, and all slag thrown out. As soon as the ingot molds are filled from the ladle, they are covered with sand to prevent loss of heat through radiation; and when the iron has hardened sufficiently, the molds are removed. As the ingots are too hot in the interior to admit of immediate rolling, they are placed in the soaking pits for about an hour. By this plan, the

ingots are uniformly heated throughout and can be rolled without reheating. At one time, the converters were arranged around circular pits so that a steel crane handled all ladles, etc. The present practice is to pour the metal into molds carried on cars, which are then pushed to the stripper where the molds are removed and the ingots placed in the soaking pit. An electric stripper, used at the Duquesne Works of the Carnegie Steel Co., is shown in Fig. 3.

Blow-holes.—The trouble experienced with broken rails by railroads, especially in countries where low temperatures prevail in

Fig. 3. Electric Stripper for Removing Mold from Ingot

winter, has demonstrated the necessity of producing sound rails. To produce sound rails means that the ingots from which the rails are made must also be sound. When the molten steel is poured into the comparatively cold molds, some of it dissolves or occludes considerable gas. This gas is apt to remain in the metal in the form of bubbles, thus forming *blow-holes* or *honeycombing*. This fault is greatest in the mildest steels and may be minimized by the addition of silico-ferromanganese or aluminum, just before the metal is poured into the mold. These seem to

deoxidize the minute quantity of iron oxide and carbon monoxide present; they also seem to increase the solvent power of the metal for gas, so that even after solidification the metal may retain in solution the gas it dissolved when melted. Preventing the formation of blow-holes, however, increases the tendency of the formation of a pipe, so that it is often better to permit these holes to form, but to control their location. This may be done by limiting the amount of manganese and silicon the metal contains and casting the steel at a relatively low temperature.

Pipes. — As the ingot contracts in cooling, a conical depression or cavity may be formed near the top. This is known as a *pipe* and is especially apt to occur in the harder steels. The formation may be partly prevented and the size of the pipe decreased by retarding the cooling of the top part of the ingot so that the metal from this part will feed the pipe that tends to form in the lower part of the mold as the metal cools. In order to confine the pipe to the very end, the ingot should always be cast in an upright position and not in a horizontal.

One method of avoiding piping is to place charcoal or some other combustible material on top of the ingot mold after it has been filled. A layer of cupola slag should be placed between the charcoal and the molten steel in order to protect the latter from the oxidizing effect of a blast of air which is directed on top of the ingot to facilitate the combustion of the charcoal. The ingot mold is fitted with a sand top, holding a supply of metal which is kept in a molten condition by the heat generated by the charcoal. This molten metal descends in the mold as contraction takes place, and eliminates any tendency toward piping which would otherwise result from the contraction that takes place during cooling.

Segregation. — A third defect is due to the different melting temperatures of the constituents of the steel. As the ingots cool, the various elements tend to separate. This fault is known as *segregation* and is greatest when the ingot is cooled slowly. Segregation may be briefly described as the tendency for objectionable impurities in steel — particularly sulphur and phosphorus — to be concentrated at the center of the ingot. The

material constituting such segregated sections is defective in strength, and when rails or structural material are rolled from ingots containing such defects, the strength of the resulting product is seriously impaired. As the inner portions are the last to solidify, there is a tendency for the sulphur and phosphorus to be concentrated in these sections.

Segregation often causes the impurities to settle around the lower part of the pipe. Under certain conditions, this tendency should be promoted rather than restrained; then the ingots may

Fig. 4. Lowering a Steel Ingot into a Blooming Mill Soaking Pit for Reheating Prior to Rolling

be made longer than desired and the pipe part with the blow-holes, pipe, and segregated material may be cut off and scrapped for remelting.

Soaking Pits. — As the outside of the ingot cools more rapidly than the inside, the inside may be too hot to be rolled or hammered when the outside is hard. The ingot must, therefore, be brought to a uniform heat, which is done by placing it in the

soaking pit (see Fig. 4). This is a covered brick-lined well in which the ingot is stood on end. It retains the heat of previous ingots, so that the excess of heat in the interior of the ingot placed in it soaks through the mass but is not lost. As a result, the steel is prepared for the mill without the consumption of any fuel. In addition, the waste of iron due to oxidation of the outer crust of the ingot is very slight, because the little atmospheric oxygen in the pit at the beginning is not renewed as it is in a furnace. Later forms of soaking pits, however, are heated by regenerative furnaces, so as to give greater flexibility to the system. In one plant the soaking pit consists of four holes, in each of which six ingots may be placed at one time.

Basic Bessemer Process. — As neither sulphur nor phosphorus is removed from the steel in the acid process, the pig iron used must not contain more than 0.10 per cent of these impurities. At the same time, the pig iron should contain about 2.50 per cent of silicon, as the high temperature is obtained mainly by the combustion and oxidation of this element. What is known as Bessemer pig iron is, therefore, smelted from hematite ores nearly free from phosphorus and sulphur. In order that the Bessemer process may be used for the phosphoric pig iron that was abundant in Europe, Sydney Thomas and Percy C. Gilchrist, in 1878, successfully developed the basic process, which is also known as the *Thomas-Gilchrist process*. In this process, a basic slag is formed by charging large amounts of lime into the converter. As the amount of lime required increases with the amount of silicon present, for economical working, the silicon in the iron must be kept low, and, therefore, cannot furnish the heat necessary for the conversion of the metal into steel. The phosphorus is converted by the heat into its oxide, which unites with the lime of the slag to form phosphate of lime. The heat from the combustion of the phosphorus provides the heat for the process. The percentage of this element, therefore, may be as high in the pig as it is possible to have it, without unnecessarily prolonging the blow.

The phosphorus cannot be eliminated in the form of a phosphate in the acid process, because iron oxide is the only base

present that will unite with the phosphoric acid to form a phosphate; and any phosphate of iron that might form will be at once broken up by the slag, producing sulphate of iron and leaving the phosphoric acid unprotected. This acid will then be reduced by the manganese and carbon of the bath and the recarburizers and the phosphorus will return to the bath.

Although the basic process can use cheaper pig iron than the acid process, it is a more costly method because of the amount of lime that must be used and the smaller output of the converter. It is also generally contended that the steel is not as reliable nor as uniform in quality, due, in all probability, to the difficulty of knowing exactly when the process is completed. Nevertheless, it is largely used in Europe for rails, rolled shapes, etc.

Description of Basic Process. — In the basic process, the blowing is divided into two parts known as the " fore-blow" and the "after-blow"; a higher blast pressure and a longer time are required than in the acid process. At the beginning of the blow, as fast as the oxides of silicon and manganese are formed, they unite with the lime to form a double silicate of lime, manganese, and iron. As the lime is greatly in excess, a high basic slag capable of holding the phosphorus in solution as phosphate of lime is formed at the start. When the silicon, manganese, and carbon are eliminated and the flame drops, as in the acid process, the blowing is continued until the phosphorus is oxidized; this is not removed very rapidly as long as carbon, silicon, and manganese are present, owing to the affinity of these elements for oxygen at a high temperature being greater than the affinity of phosphorus. The combustion of the phosphorus produces a great deal of heat and the iron is protected from oxidation by the phosphorus as long as very much of it is present.

When charging the converter, the lime is placed at the bottom and the molten metal is poured upon it. Sometimes this lime is preheated; at other times, coke or coal is charged with it and the blast is turned on sufficiently to burn the fuel and heat the lime. During the first part of the blow, the metal should be as hot as possible so as to prevent slopping; but before the steel is poured, the temperature should be reduced. During the

fore-blow, the conditions of the charge are shown by the flame and the temperature is regulated by varying the blast or by the addition of scrap. In the after-blow, the conditions are judged entirely by the amount of air blown through the metal and no attention is paid to the flame or other indications. This period is determined by experiment for different percentages of phosphorus, but is approximately one-half the length of the fore-blow.

Basic Pig Iron. — In the basic process, the pig iron used should contain from 2 to 3 per cent of phosphorus, less than 0.50 per cent of silicon, from 0.75 to 3 per cent of manganese, and not more than 0.10 per cent of sulphur. In fact, when very low sulphur steel is to be made, the sulphur in the pig iron should not exceed 0.05 per cent. The carbon is usually from 3 to 3.50 per cent and is in the combined form. The manganese in most cases ranges from 1 to 2 per cent. This element furnishes some of the heat at the beginning of the blow, as the low silicon content will not give enough heat at this stage; besides, the manganese has the tendency to desulphurize the metal, which is a great advantage, as the basic Bessemer pig iron is likely to be high in sulphur because of the low silicon content.

Utilization of Slag. — The large amount of phosphoric acid in the slag obtained from the basic process makes it a valuable fertilizer and it is largely used for this purpose, especially in Germany. For this purpose, the slag is ground exceedingly fine in a bell mill and applied in this form. The phosphate, however, is insoluble so that only a part of it is available as plant food. When the pig iron is not high enough in phosphorus, the slag is returned to the blast furnace and resmelted. In this case, the high percentage of lime and magnesia, usually from 55 to 60 per cent, makes it valuable as a flux; besides, the iron and manganese it contains are recovered. The more economical method of disposing of the slag depends entirely upon local conditions, as to the cost of the flux and the value of the slag as fertilizer.

Mixers. — Converters were formerly charged with metal that had been melted in a cupola. In order to avoid the cost and

labor of this remelting of the pig iron, many attempts have been
made to use the molten blast-furnace product. The steel pro-
duced, however, varied greatly in quality, because of the differ-
ence in the various charges. This trouble is eliminated with the
use of a *mixer*. This device is a large steel-plate firebrick-lined
structure. The metal from the blast furnace is poured into this
and held until wanted. As it holds from 150 to 200 tons, it
contains the metal from several heats, so that the metal for the

Fig. 5.   Pouring Molten Iron from Mixer into Ladles for Transpor-
tation to Open-hearth Furnaces or Bessemer Converters

converters or open-hearth furnaces is more uniform in com-
position. Besides reducing the amount of metal lost in the
blast, the mixer furnishes the metal exactly as it is wanted and
in the proper amount, for the ladle that carries the metal to
the converter is placed upon a scale, and the pouring from the
mixer is stopped when the required weight is in the ladle.   Fig.
5 shows molten iron being poured from a mixer into ladles for

transportation to either Bessemer or open-hearth furnaces. Cupolas are usually operated in connection with the mixer to supply part of the metal, should the blast-furnace output fall below the converting capacity.

Physical Characteristics of Bessemer Steel. — The Manufacturers Standard Specifications for Structural Steel, as revised April 21, 1914, cover three classes of steel: Class A, which is used for railway bridges and ships; Class B, which is used for buildings, highway bridges, crane sheds, and similar structures; and Class C, which is used for structural rivets. Of these, only Class B may be made by the Bessemer process, in which case it is specified that the phosphorus content must not exceed 0.10 per cent. The specifications for physical properties require for this Bessemer steel a tensile strength of from 55,000 to 65,000 pounds per square inch; a maximum yield-point of one-half the tensile strength; and a minimum percentage of elongation in eight inches equal to 1,400,000 ÷ tensile strength. The elongation in two inches should be a minimum of 22 per cent. The steel may have a tensile strength up to 70,000 pounds per square inch, provided the elongation is not less then the percentage required for a steel having 65,000 pounds per square inch tensile strength.

CHAPTER VIII

OPEN-HEARTH STEEL

WHILE the Bessemer process makes it possible to produce steel cheaply in large quantities, so that it replaces wrought iron for many purposes, the process can be used for making steel only from pig iron made from certain ores. In the acid Bessemer process, only pig iron with a low phosphorus content can be used, while in the basic Bessemer process, the phosphorus content must be considerably higher, there being an intermediate stage of ore and pig iron which has too much phosphorus for the acid Bessemer process and too little for the basic. This condition led to the development of the open-hearth process which is now commercially the most important of the steel-making methods.

General Description of Open-hearth Process. — In the open-hearth process, which is somewhat similar to the puddling process for producing wrought iron, but operated on a much larger scale, the impurities are removed from a bath of pig iron held on the hearth of a regenerative furnace, the iron being exposed to the action of the flame from the fuel, which generally consists of a mixture of producer gas and air. The charge which, besides pig iron, consists of a mixture of scrap iron, scrap steel, and iron ore, is exposed to the intense heat produced by the fuel for seven or eight hours, the process being stopped when the bath of iron has the right proportions of carbon, as determined by chemical analysis. The steel may then be withdrawn from the furnace and either poured into ingots and rolled into shape, or cast into molds, producing steel castings. The furnaces generally have a capacity of from 40 to 50 tons of molten metal. Furnaces having a capacity as high as 200 tons have been made. While in the Bessemer process only pig iron can be used, it is practicable in the open-hearth process to also use scrap of wrought iron and steel, because of the high temperature produced in the fur-

nace by the burning of gas which is preheated to a temperature
of about 1000 degrees F. before entering the combustion cham-
ber, by passing it through the regenerative chambers of the fur-
nace. The open-hearth process produces a more uniform and
reliable steel than the Bessemer process, and the latter steel has
been largely replaced for more important purposes by the open-
hearth steel. (See "Tonnage Produced by Bessemer and
Open-hearth Processes," in Chapter VII.)

Basic and Acid Processes. — The open-hearth process may
be either acid or basic, according to the character of the lining.
The basic process is dephosphorizing, burnt lime being added
to the charge to remove the phosphorus. In the acid process,
no lime is required, but the metal charged must be low in phos-
phorus. Except for this difference, and with the exception of
the lining of the furnace, both the acid and basic processes are
practically the same. In the basic process, the furnace lining is
neutral, while in the acid process, the lining is siliceous. The
acid process is the faster and cheaper process, but the difference
in cost is offset by the greater cost of pig iron and scrap free
enough from phosphorus; consequently, a very large percentage
of the open-hearth steel produced in the United States is basic.
The gross tonnage in 1916 was 29,616,658 tons for the basic
process and 1,798,769 tons for the acid process, according to the
American Iron and Steel Institute. Included in the tonnage
given for the basic open-hearth process, there were 3,436,457
tons of "duplex steel" ingots and castings which were made from
metal partly purified in Bessemer converters and finally purified
in basic open-hearth steel furnaces.

Development of Open-hearth Process. — Sir William Siemens
made steel in an open-hearth furnace, in 1862, by melting iron
ore in a bath of pig iron. The ore, when reduced in the furnace,
furnished the oxygen necessary for oxidizing the carbon, silicon,
and manganese in the pig iron. The same method had been
tried by Heath in about 1845, but he did not succeed, because
he could not produce sufficient heat to carry on the process.
The invention of the regenerative furnace by Siemens in 1861
made it possible to obtain the required heat, and, in 1864, the

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French steel-makers, Messrs. Martin, patented a process of making steel by melting pig iron and scrap in a furnace heated by the Siemens regenerative method. On the European continent, the process is generally now known as the "Siemens-Martin process" or simply the "Martin process." In Great Britain, it is known either as the "Siemens-Martin" or the "open-hearth process," the last name being the most generally used. In American practice, the name "open hearth" is almost exclusively used. Both the pig iron and ore (the Siemens) and the pig iron and scrap (the Martin) processes are combined in general American practice.

Comparison of Bessemer and Open-hearth Processes. —The open-hearth process differs from the Bessemer in that steel of any percentage of carbon can be made, while the Bessemer process can be used only for the manufacture of medium and low-carbon steels. As it does not depend upon the oxidation of the impurities for the heat necessary for its working, the open-hearth process can utilize pig iron and scrap of a wide range of analysis; besides, the operations are under greater control than in the Bessemer converter; there is less danger of the oxidation of the metal; the product is more uniform and reliable; the yield of ingots, compared with the amount of metal charged, is higher; and samples for both physical and chemical tests can be taken while working.

Open-hearth Furnaces. — There is practically no difference in the acid and basic furnaces. Either may be stationary or tilting, but in each case the furnace consists of a rectangular hearth connected at the ends with regenerative chambers. The capacity of these furnaces varies from 5 to 15 tons, for special steels, up to 60 and 80 tons, for standard grades. In a furnace producing 50 tons of ingots at a time, the hearth is 33 feet long and 14 feet wide. Owing to the difficulty of handling the metal in larger furnaces, those from 50 to 60 tons capacity are usually preferred. With larger furnaces, there is often trouble in pouring; either the metal must be too hot at the beginning of the pouring to make good steel or, if at the proper temperature when first poured, it will be too cold at the end of the pouring; be-

sides, the ingots will require reheating before they can be put through the rolling mills.

It is of great importance that the hearth be well proportioned. It should be long enough to insure complete combustion over the hearth; otherwise some of the gases will burn in the ports and upper checkerwork. For economical working, it has been
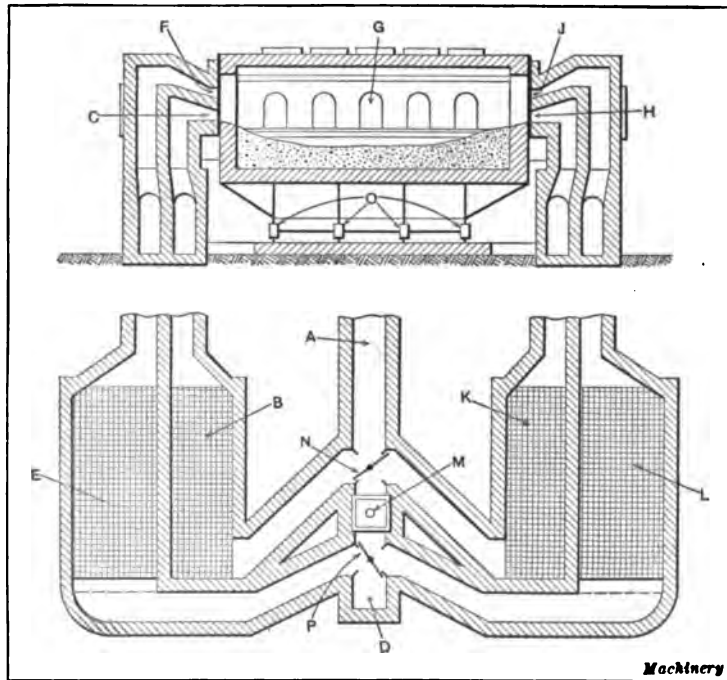
Fig. 1. Sectional View of Open-hearth Furnace

found that the maximum width is about 15 feet and the length is from two to two and one-half times this dimension. It should be shallow enough to promote thorough heating and reasonably quick working of the bath, yet deep enough to minimize the oxidation of the metal and thus avoid over-burning and a reduction in the output. For these reasons, the depth is usually from 15 to 20 inches.

Description of Open-hearth Furnace. — In Fig. 1 is shown a section of an open-hearth furnace, together with a plan view

in section of the regenerative chambers and flues. After the
furnace is charged, the gas and air in a gas-fired furnace are
turned on. The gas enters the flue A, passes through the gas
chamber B where it is heated as it passes through the checker-
work, and then enters the furnace through the ports C. At the
same time, air from flue D passes through the flues into the air
chamber E and then through port F into furnace G, where the
combustion takes place. The waste gases then pass through the
ports H and J into chambers K and L, which are heated by them
before they pass out through the chimney M. When chambers
B and E become cooled, dampers N and P are shifted, forcing
the gas through chamber K and the air through chamber L.
The waste gases pass to chimney M through chambers B and E,
which are now heated. In this way, the gas and air are always
preheated by passing through the chambers that have previously
been heated by the waste gases, and, by alternately turning on
the air and gas from the left or the right, one set of chambers is
constantly being heated; hence, the air and gas can always be
preheated, throughout the operation, by merely making use of
the heat in the exhaust gases. In the furnace shown, the steel
is discharged by tilting the hearth by means of a hydraulic ram
which causes the furnace to rock over the rollers O.

Making the Acid Hearth. — The entire bottom and hearth
are built on and supported by a pan of heavy riveted steel plates
carried by beams or channels resting on piers entirely inde-
pendent of the rest of the structure. In the case of the acid
bottom, this pan is covered with two or three layers of silica or
clay brick, preferably the former, while other courses are stepped-
up at the ends and sides, so that the thickness of the sand bottom
will be approximately uniform over the entire hearth. The
furnace is then gradually brought up to nearly its working tem-
perature, and the bottom is covered with a thin layer of sand.
After this has sintered, more sand is thrown on, in thin layers,
sufficient time being allowed for each layer to set perfectly.
This process is continued until the hearth is from 16 to 24 inches
thick on the bottom and sides, is saucer-shaped, and the sides
are carried up about a foot above what is the level of the metal

bath. Sometimes, the bricks are covered with a thin layer of sandstone or granite chips, which are softened by the heat and glaze the bricks. The completed bottom is often washed down with a charge of open-hearth slag.

The sand should be silica sand with just enough ferrous oxide and alumina to make it "set," or partly fuse, at the full heat of the furnace. Owing to the difficulty of obtaining such a sand, a common practice is to mix a pure silica sand with a sand that contains a larger proportion of ferrous oxide and alumina than is desired, in the proportions necessary to give the required mixture. Quite frequently sands of different fusing points are mixed as the object is to obtain a bottom that will not be eroded by the iron at the melting temperature.

Making the Basic Hearth. — The basic hearth is made by covering the pan with two or three courses of clay brick and laying upon these two or three courses of magnesia brick. The sintered sand bottom is then built upon this. Sometimes the magnesia and clay bricks are separated by a layer or two of chrome brick, which retards the "breaking out" of the metal should the bottom be cut through, and usually allows the charge to be tapped out before the "break-out" actually occurs. The complete bottom is then given a wash heat of basic slag or scrap, which is allowed to soak into the bottom. Sometimes dolomite is used for the basic hearth, but magnesite is preferred, as it makes a much denser bottom and one that can be relied upon to stay in place when once set and soaked full of slag, while dolomite bottoms frequently cut through and come up in patches.

Open-hearth Furnace Walls. — The end walls, known as "blocks" or "bulkheads," of the open-hearth furnace are from 4 to 6 feet thick, because they contain the flues or passages from the regenerators. These walls were formerly built solid, but the present practice is to make them of steel frames that are heavily faced with brick. This construction has been found to be the most economical to maintain. In the basic furnace, these walls are faced with magnesia brick up to the ports. In the acid furnace, they are faced with silica brick.

The side walls are about 15 inches thick. In the acid fur-

nace, the walls are built of silica brick; but in the basic, they are made of magnesia brick up to a few courses above the slag line, above which point they are made of silica brick. Sometimes one or more courses of chrome brick are placed between the silica and magnesia brick to prevent any fluxing action between the two, should the temperature rise above the normal. Sometimes steel or iron plates are placed outside the front and back walls of the furnace to strengthen them. This construction is objectionable, however; as far as possible, the walls should be bare. When the plating is used, it is almost impossible to patch the walls when they become thin.

Roof of Open-hearth Furnace. — The whole structure is held together by heavy beams, called " buckstays," set perpendicularly along the sides and ends and connected by tie-rods and turnbuckles. This arrangement permits the quick and easy adjustment of these parts to allow for contraction and expansion of the walls. The roof is supported by heavy channels that form part of the framework, although at one time it was permitted to rest upon the walls. This latter construction was found faulty, because the walls could not be patched without danger of damaging the roof; besides, the weight of the roof resting on the walls was likely to distort them, and at times caused the walls to fall when they were partly cut through by the metal. By the present method, the walls may be repaired or renewed without disturbing the roof. Quite frequently, the roofs are arched from port to port as well as across the furnace, which insures stability of construction as well as providing for expansion.

The roof is invariably built of silica brick and should be sufficiently high to prevent its being burnt away by the impinging flame from the ports. Its thickness varies with the size of the furnace, but it is generally from 8 to 13 inches. In the earlier furnaces the roof was made comparatively low in order to keep the flame close to the bath, but this plan has been abandoned because of the excessive repairs made necessary by the rapid burning away of the roof when so arranged. Still, the distance from the hearth to the roof should not be too great; sometimes

the working of the furnace has been improved by reducing this height.

Ports of Open-hearth Furnace. — The successful operation of an open-hearth furnace depends largely upon the construction of its *ports*, which is the name given the openings through which the air and gas are admitted.. These ports are filled alternately with the inflowing gas or air and the outflowing gases of combustion, which contain incandescent particles of ore, limestone, slag, etc. They are generally built of silica brick. They may have water-cooling plates placed around them, but paving the port with magnesia brick or fine chrome ore and daubing the face with ore, however, seem to be among the most satisfactory preserving methods. The position and pitch of the ports must be carefully planned. They are connected by " up-takes" with the regenerative chambers and are so arranged that the air and gas mix and ignite as soon as they pass into the melting chamber. The air is placed above the gas and thus protects the roof from the intense heat generated, while the gas underneath prevents the air from directly striking the charge and thus causing undue oxidation. As the air is heavier than the gas, this arrangement also causes the flame to be thrown toward the bath and away from the roof.

The ports are usually placed so that the gases will meet from two to five feet above the bath. If they meet too near the bath, the combustion will be incomplete, because the gases will be cooled by the bath. If they meet too high above the bath, the most intense temperature will be at a point so high that the roof and sides will be damaged. In addition, if the pitch is too flat, the flame will not be brought down sufficiently on the metal and the combustion will be too high in the melting chamber and will distort the brickwork. If the pitch is too steep, the flame will strike the bath before the combustion is complete; besides, the heat will tend to concentrate in one place instead of being evenly distributed over the hearth. In most large furnaces, there is one gas and one air port at each end; but some furnaces have two air and one gas port, while others have two gas and two air ports at each end. In other furnaces, still other arrangements of the ports are made.

Regenerators. — The gas and air chambers, or *regenerators,* formerly were placed directly underneath the furnace; but, owing to the difficulty of making repairs and of keeping the brickwork gas-tight and air-tight, and the delay and expense caused should the metal cut into the checkerwork, these chambers are now separated from the furnace. Both air and gas chambers are made of checkerwork so arranged as to expose a large surface to the gas. At one time, they were made of the same size, but the present practice is to make the air chamber one and one-half times the size of the gas chamber, because that is the proportion in which the air and gas must mix for their proper combustion.

The gas chambers may be placed on either side of the air chambers and for a 60-ton furnace should be from 13 to 18 feet high and have a capacity of 90 cubic feet per ton of steel. Sometimes the bricks are laid so as to give a number of small horizontal flues in the chamber, but more generally they are staggered. By this plan, the waste gases are brought into more intimate contact with the bricks, assuring a better absorption of heat from the waste gases and more thorough reabsorption of this heat by the unburned gas and air when the currents are reversed. The openings between the bricks and the exposed ends must not be so large that the surface will not absorb enough heat from the waste gases nor sufficiently heat the gas or air when the current is reversed. On the other hand, they must not be so small that the openings will clog rapidly with flue-dust. In many cases, the checkerwork is built of standard 9-inch brick and the openings are approximately $3\frac{1}{2}$ by 4 inches wide.

"Slag pockets" should be placed at the bottom of the uptake. These are open chambers in which fine particles of ore, slag, and limestone settle before the gases enter the checkerwork. This arrangement reduces the tendency of the small openings to clog and thus improves the working of the furnace. Manholes and clean-out doors permit the rapid cleaning of these.

In many instances the checkers are built of first quality clay brick, although in some plants the ten or twelve top courses are made of silica brick. The present tendency, however, is to

use silica brick throughout, or to build the five or six top courses of magnesia brick. It is claimed that the silica bricks clog less rapidly than the clay and do not take on a carbon coating as quickly. Silica brick also expands, thereby holding everything tightly as the furnace is heated.

Operation of Regenerators. — When the furnace is in operation, the air and gas enter through the chambers and ports in one end and ignite as they mix in the melting chamber. The waste gases of combustion then pass through the ports in the other end and passing through the gas and air chambers enter the chimney. In their passage through the flues and checkerwork, the waste gases give up their heat and pass up the chimney comparatively cool. After a given time, usually fifteen or twenty minutes, the valves are reversed and the air and gas pass through those chambers that have just been heated and the waste gases pass through and heat the chambers through which the air and gas have just passed. With each reversal of the gases, the temperature of the air and gas is raised and as the temperature of the bath is also increased, especially toward the end of the heat, unless the gas and air are carefully regulated, the furnace "will melt itself down" in a short time.

Oil as a Fuel. — Open-hearth furnaces must be heated by a gaseous fuel. Oil vaporized by steam or air is one of the best fuels, but its use is restricted to those localities where oil is plentiful and cheap. Oil requires no preheating and is of high calorific value, is regular in quality, and permits a uniform operation of the furnace; but its flame is short, and unless care is taken, the roof will be cut out and the metal of the bath over-oxidized.

Natural Gas. — Natural gas is considered the ideal fuel. It is low in cost, has no sulphur, is clean and convenient to use, requires no preheating, has a high calorific value, and its purity produces a pure steel or allows the use of poor raw material. Its use, however, is restricted to those regions where it is plentiful and cheap; although it has been piped to plants two hundred miles from its source. Natural gas is a mixture of methane and other hydrocarbon gases and hydrogen. It is found principally

in the western part of Pennsylvania and the adjacent parts of Ohio and West Virginia. Its pressure at the wells, which vary in depth from 1000 to 4000 feet, is frequently so great as to render the gas difficult to control, but in the lines a pressure of from six to ten ounces per square inch is maintained. Its calorific value averages from 970 to 1010 B.T.U. per cubic foot.

As neither oil nor natural gas requires preheating, regenerative chambers are used for the heating of the air alone. At first an effort was made to preheat natural gas, but it was found that the gas was reduced to hydrogen or lower hydrocarbons which have less heating value than the original gas. In addition, carbon was deposited in the chambers in the form of a hard glassy coke, the heating value of which was lost, as this burned on the reversal of the furnace, and the products of its combustion passed up the chimney instead of into the furnace.

Producer Gas. — Owing to the limited areas in which oil and natural gas are available, artificial gas must be used in most open-hearth furnaces. While any artificial gas will do, theoretically, producer gas is the one used. One advantage of the gas producer is that inferior kinds of fuel may be utilized, the one essential being that the fuel is a good gas coal that does not contain too much sulphur. The amount of tar present depends upon the coal. While the tar furnishes from 6 to 12 per cent of the calorific value of the gas, some of the tar is deposited in the gas main, valves, and flues, and so is not burned in the furnace. The calorific value of producer gas is from 120 to 145 B.T.U. per cubic foot. Producer gas is generally made by burning bituminous coal in a producer.

Acid-furnace Charge. — In the acid process, a large proportion of the charge is steel or wrought-iron scrap and the rest is pig iron and iron ore. The quality and quantity of the scrap and the analysis of the pig iron determine the proportion of each. The scrap may be crop ends of bolts, rails, structural sections, machine-shop turnings and borings, etc.; but as neither sulphur nor phosphorus is eliminated in the process, the charge must contain no more of these than is permissible in the steel. In order to indicate the relative amounts of carbon, the pig iron

is frequently referred to as "hard stock" and the steel and wrought-iron scrap as "soft scrap." If the charge contains too much scrap, the heat will be so low in manganese, silicon, and carbon that it will be hard to work; besides, there will not be enough slag formed to adequately protect the bath so that the oxidation losses will be high. On the other hand, pig iron high in silicon with a small proportion of scrap will give the bath such a heavy slag covering that it cannot be penetrated by the heat. Pig iron that is very low in silicon may be used without other additions.

The ore used is a red hematite that is as free as possible from all impurities. It should be in lumps heavy enough to sink through the slag and the bath of metal, so as to reach the elements it is to oxidize. It should contain as much oxide of iron as possible, so that the most work may be done with a given weight of ore.

Determining Proportions of Charge. — In general, the charge is so adjusted that when melted the bath contains from 0.30 to 0.60 per cent of carbon above the point actually required in the steel. If too little pig iron is used, all the carbon, silicon, and manganese in the bath will be oxidized before the metal is ready to tap. As a result, the metal will become pasty and oxide of iron will be rapidly formed, thus wasting the metal by increasing the melting loss; besides, if the slag is not acid enough, the ferrous oxide will form ferrous silicate, which will score the bottom, while the oxides introduced into the bath will be difficult to remove and will injure the steel, making it "wild" to handle in the furnace and ladle. The remedy for too little pig iron in the bath or a heat melting "low" or "soft" is to add pig iron, or "pig up," to give sufficient carbon and silicon to bring the bath to a boil and obtain the necessary temperature to tap the heat. This, however, causes a loss of time, because each addition of pig iron lowers the temperature of the bath and requires more pig than if the metal were added in the first place. If too much pig iron is charged, no harm is done to the quality of the steel as the bath is then high in carbon and possibly contains some silicon and manganese. These can be "boiled out"
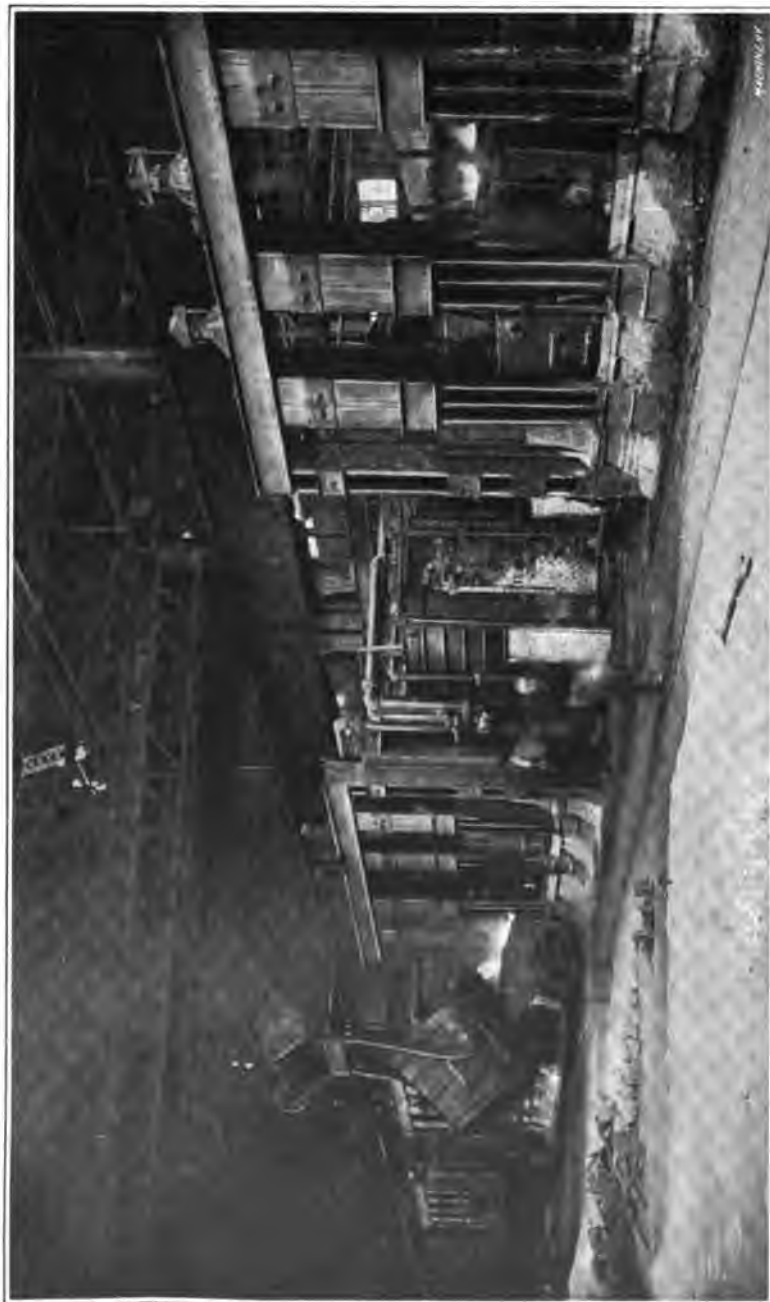
Fig. 2. Pouring Molten Iron from a Ladle into Open-hearth Furnaces at Homestead Works of Carnegie Steel Co.

but the usual method is to add ore, which hastens the oxidation of the impurities.

The proportions of the charge are fixed by a study of the reactions that occur. The silicon and manganese are deoxidized to form, with the manganese and iron in the bath, a double silicate of manganese and iron, which rises and forms the slag; the carbon is deoxidized to carbon monoxide, and then to carbon dioxide, in which form it passes off.

Method of Charging the Acid Furnace. — In the acid process, the iron is charged first, generally in a molten condition direct from the blast furnace (after being placed temporarily in the mixer) so as to protect the hearth from the oxide of iron formed by the oxidation of the scrap by the flame. Should this oxide come into contact with the bottom of the hearth, it will form a silicate of iron which will rapidly cut the bottom. The cutting, or "scorification," of the bottom not only may cause a hole to be cut through the bottom of the hearth, but the sand may be so impregnated with iron that its refractory power and ability to withstand the action of the metal is lessened. One of the open-hearth furnaces shown in Fig. 2 is receiving a charge of molten iron from a ladle.

Sometimes, when charging the furnace with pig iron in the form of bars, only a part of the pig iron is placed on the bottom of the hearth, the rest being placed on top of the scrap. Melters using this plan contend that the pig iron on top of the scrap will melt first and its carbon, silicon, and manganese will protect the iron of the scrap from excessive oxidation.

The charging should be done, if possible, at one time. Sometimes, however, pig iron is allowed to heat, or even partly melt, before the scrap is added. It is claimed that by this practice the stock has time to heat up as added, so that the melting goes on much faster. Other melters contend that the slow charging cools off the furnace, because the doors are opened so long; besides, the oxidation loss is greater and more gas is used. If a furnace is properly designed, its regenerative capacity should be such that the heat in the checkerwork will prevent the furnace being chilled by too rapid charging.

Charging Machines. — Although small furnaces are charged by hand, machines must be used in the case of larger ones. These do the work in about one-third the time and charge more continuously, as charging is the hardest and hottest part of the furnace work. The machines also reduce the production cost, as one machine will charge five or six furnaces, each of which would otherwise require at least three or four men. A charging machine consists of a four-wheeled truck that carries a heavy framework, the girders of which extend to the face of the furnace. From these girders is suspended a carriage that carries and operates a ram. The stock for charging the furnace is placed in steel-plate boxes. One end may be made of cast iron, but the end that is fastened to the ram must always be made of cast steel. This end is arranged so that it can be quickly attached to and detached from the ram, and the sides of the boxes are slightly flared so that the stock will readily drop out when the boxes are turned over. The boxes are filled in the stockyards and placed, in sets of three or four, upon small narrow-gage cars that run just in front of the furnace. When the furnace is to be charged, the cars containing the boxes are run into position and the charging machine is placed directly in front of the furnace door. The carriage is then run forward until the ram is in position for attaching one of the stock boxes to its end. As soon as this is attached, the ram is run into the furnace and turned about its axis until all the stock has fallen from the box, when the motion is reversed and the ram is withdrawn. As soon as the empty box is replaced by a full one, the ram is again inserted in the furnace. The operation of lifting, discharging, and replacing a box occupies about a minute, so that about 50 tons of material may be charged into a furnace in about an hour. At one time this machine was operated by steam or compressed air, but the present machines are operated by electricity, separate motors being employed for the different motions. A "high-type" open-hearth charging machine made by the Wellman-Seaver-Morgan Co., Cleveland, O., is shown in Fig. 3.

Operation of Acid Furnace. — When the furnace is first put into operation, the flame, as a rule, is kept smoking by supply-

ing less air than is necessary for the complete combustion of the gas. This plan prevents the oxidation of the scrap at the beginning of the heat; the pig iron is protected from oxidation to a large extent by its impurities. Many furnace men, however, favor melting as quickly as possible, even if the oxidation loss is great. In the operation of the furnace, the aim is to have an even flow of gas, but to use the minimum amount. The ideal flame is free from spots and flickering, long enough to heat the whole length of the hearth. If the flame is too short to reach the farther end of the furnace, only the charge at one end of the

Fig. 3. "High-type" Open-hearth Charging Machine

hearth is heated, and that is badly oxidized; if the flame is so long as to be still burning as it enters its farther port, considerable gas will be wasted. The proper flame will melt the stock rapidly and uniformly. A swift short flame dragged along by the draft of a wide-open stack damper and fed with too much air will "glaze" the stock so that it will melt chiefly at the top of the pile. Such melting delays oxidation of the metal, wastes iron, and makes the steel "wild" from an excess of dissolved oxide.

In American practice, the charge is usually so proportioned that the silicon and manganese are oxidized when the charge is

melted. Generally only about one-third of the carbon is oxidized at this time, because its affinity for oxygen is not as great as that of the other elements. If the silicon and manganese in the charge are low, more of the carbon will be oxidized. In a normal heat for soft steel, manganese, silicon, and carbon are eliminated in the order in which they are named and in accordance with their affinity for oxygen. When the charge is melted, the bath is well stirred with a bar or "rabble" and the height to which the slag boils over the bar as it is moved about is noted. The colder and softer the metal, the higher will be this boil. The boiling produced by this "rabbling" frees the steel from oxides.

When the silicon and manganese have been almost entirely removed and the carbon has been brought down to about 0.60 per cent, the ore is added to the bath. The amount that may be added at one time depends upon the condition of the bath. If the slag is cold, the addition of the ore chills the bath, while hot slag permits the ore to be added quite rapidly; yet care must be taken that the ore is not added so rapidly as to cause the bath to boil over. The boiling increases in violence quite slowly until a certain point is reached, after which the addition of one or two lumps of ore will cause the whole bath to boil so violently that the slag and metal will run out of the door. At the same time a great amount of carbon monoxide will be suddenly evolved and in burning to carbon dioxide will so fill the furnace with gas that the flames will pour from all openings. As soon as enough ore is charged to bring the carbon content to the desired point, the bath should be allowed to become quiet before it is tapped.

Should too much ore be added to the bath, the metal may become practically carbonless before it has had time to become hot; to prevent its freezing, pig iron or ferrosilicon must be thrown in. Ferrosilicon is used when the bath is hot, but losing its carbon too rapidly; pig iron is used when the bath must be heated without the elimination of more carbon.

Recarburizing the Metal. — It is possible to calculate the proportions of a charge so accurately that the amount of ore

necessary to oxidize the impurities is easily determined. The working conditions, however, vary so much that the steel obtained by this method would not generally be uniform nor of the desired quality; therefore, it is customary to oxidize the bath to a certain point and then raise the carbon content by recarburization. The addition may be made to the metal in the hearth just before it is tapped or as it is being run out into the ladle. Any manganese or silicon that the steel is to contain must be added at this time, if all manganese and silicon that were in the charge were removed by oxidation.

The recarburizer most generally used in the acid open-hearth process is ferromanganese. This supplies the manganese desired, reduces the oxide of iron remaining in the bath, and removes the free oxygen held in the gaseous form. It mixes better when added to the metal in the furnace, but there is said to be a greater loss of the manganese than when added in the ladle. When the heats are small, or high manganese or silicon steel is being made, the ferromanganese is heated to redness before it is added to the molten metal; for medium and large-sized heats, however, the recarburizer is not usually heated, but is thrown into the ladle so as to mix with the stream of the metal.

Spiegeleisen, ferrosilicon, silico-spiegel, or silicon carbide, pig iron, and powdered coal and coke are also used, especially for high-carbon and special steels. Aluminum is sometimes added to the metal when it is in the ladle or after it has been poured into the ingot mold in order to deoxidize or neutralize the metal and thus minimize the formation of blow-holes. Aluminum, however, has a tendency to increase the size of the pipe or shrinkage cavity in the ingot, as it localizes the shrinkage.

Testing the Metal. — The successful operation of an open-hearth furnace requires that tests be made at regular intervals to determine the condition of the metal and that the proper temperature be maintained. As no apparatus is used for measuring the temperature, the melter must become skilled in determining the temperature of the melting chamber by the appearance of the roof and side walls and the flame and slag, as he observes these through the blue glass in the peep holes. The

temperature of the bath is determined by the action of the bath on a metal rod.   If the bath·is hot, the end of a bar used to stir the bath will be melted off quite square; if the bath is cold, the end of the rod will be tapered.   The rod must be thrust quickly through the slag or it will be coated with slag and protected from the action of the bath and thus give misleading indications. The "feel" of the bath as the bar is stirred in it also shows the

Fig. 4. Seventy-five-ton Ladles placed at Open-hearth Furnaces to Receive the "Heat" of Molten Steel — Homestead Works of Carnegie Steel Co.

condition; sometimes the surface is of the proper temperature while the bottom contains partly melted stock.

A common custom is to dip up with a test spoon some of the metal from the bottom of the bath as soon as all the stock is melted.   This metal is at once poured into a small test mold. The melter then estimates the amount of carbon in the bath and the amount of ore required to reduce the carbon to the desired point by the fracture of the test piece.   Any metal that may be left on the spoon when the mold is filled is slowly poured off so that its temperature may be judged.   If the metal pours

off clean to the last drop, it is very hot; the more it tends to cling to the spoon the colder it is. A little of the slag that adheres to the handle of the spoon is saved from each heat. These samples show, by the changes in the color, the progress in the elimination of the iron oxide. When the melter thinks that enough ore has been added to the bath, he makes another test and in one-half hour, a third. An experienced melter can usually determine the carbon as shown by the fracture within two or three hundredths of a per cent, in samples containing less than 0.20 per

Fig. 5. Casting Crew on Open-hearth Pouring Platform filling Molds
with Molten Steel tapped through Bottom of Ladle

cent of carbon. Above this point, there is a greater liability to error, which increases as the carbon increases. The character and temperature of the metal are also shown by the way it pours, its fluidity, and the sparks given off. The test pieces also show the contraction of the steel on cooling.

Making the Ingots. — When the steel is ready, the molten metal is drawn into a ladle and poured into the molds. (See Fig. 4.) These ladles are usually made of heavy riveted steel plate lined with two courses of firebrick, and hold from 30 to

75 tons of metal. They are carried by cranes and the metal is poured from them through the bottom as shown in Fig. 5. By this plan, the metal is kept under better control than when the metal is poured over the lip, and the slag is prevented from passing into the molds. Sometimes the molds are placed in rows in the charging pit; but more commonly they are placed on cars, which are then run directly into the rolling mill. Fig. 6 illustrates how test samples are obtained at the open-hearth pouring platform.

In ordinary practice, the slag is held in the furnace until all the heat is tapped, when it runs out and forms a covering for the metal in the ladle, thus protecting it from loss of heat. Sometimes part of the slag is run off into a slag hole under the tap hole.

Basic Furnace Charge. — The charge of the basic furnace differs from the charge of the acid furnace in that it contains lime, as phosphorus and sulphur are to be removed or reduced. Because of the irregularity in the elimination of sulphur, some mills will allow no more sulphur in the charge than is permissible in the ingot. Because of the difficulty of removing it, the sulphur in the pig iron and scrap should be as low as possible, and never over 0.05 per cent in the pig.

The lime may be charged in the form of limestone, or calcined oxide commonly known as "lime." When the limestone is charged, as is the common practice, and is calcined on the open-hearth, the resulting liberation of carbon dioxide makes the bath boil and insures a lively reduction and mingling of the elements; but the heat required for this calcination of the limestone appreciably retards the operation of the furnace. Besides, there is a greater tendency for the slag to boil and the metal to escape in the form of gas. Sufficient lime must be charged so that the slag will be basic enough to supply a base with which phosphorus can combine and form a stable compound. While the phosphorus can unite with the iron oxide, the same as with the calcium oxide, the iron oxide will be again reduced and the phosphorus will be returned to the bath. The limestone must be as pure as possible, for whatever silica it may possess must

first be satisfied by the lime, before the lime is available for the
oxidation of the bath.   In order that the amount of lime may be
kept down as much as possible and the amount of slag kept low,
the pig iron charged should not contain more than one per cent
of silicon.

Method of Charging the Basic Furnace. — In the basic proc-
ess, the hearth is generally covered by the limestone before the

Fig. 6.   Obtaining a Sample at the Pouring Platform

pig iron and the scrap are charged; the charge, however, may
consist entirely of molten iron directly from the blast furnace.
Sometimes only part of the limestone is charged at first and the
rest is added in small quantities as the heat proceeds, while the
order of charging the pig iron and scrap may also be reversed.
The chief advantage of charging all the limestone first is that it

affords more protection to the bottom of the bath and that, as the stone is decomposed, the carbon dioxides and calcium oxide pass through the pasty mass and thus help the action of the bath. The objection to this practice is that the lime sometimes sticks to the bottom of the hearth, thus reducing the melting space. This can be avoided with a little care.

When molten pig iron is used, the scrap is placed upon the limestone and the molten iron is poured from a ladle on top of it. The advantage of using hot metal is that less time is required for the heat, thus increasing the output of the furnace; besides, the time and labor of making the pigs are avoided. Usually the molten metal is not poured into the furnace until the scrap has been heated enough for it to begin to "drip."

Operation of Basic Furnace. — In order to eliminate the phosphorus and sulphur, it is essential that a basic slag be formed from the start. The slag produced when the heat is melted (unless it is very hot) is sluggish, basic, and contains lumps of limestone; but, as a rule, the phosphorus is largely eliminated. Usually a test of the bath is taken at this time to determine the amount of ore that must be added to produce the steel desired, and also to determine the phosphorus content. If the test piece is too high in phosphorus, its fracture will show a crystalline formation known as the "phosphorus cross." As soon as all the slag is melted, sufficient ore must be added to oxidize the carbon and produce a vigorous boiling; but as the carbon approaches the desired point, lime is added to keep the slag basic so as to promote the elimination of the phosphorus. The progress of this elimination should be watched closely, as often it is sufficiently advanced at the time the carbon is low enough and the heat is hot enough to tap. As in the acid process, the ore should be introduced early and allowed to work until its iron oxide has been used, as far as possible, in eliminating the silicon, manganese, and carbon from the bath. The best metal is produced by working heats for some time after the effects of the ore are worn off, to reduce the iron oxide in the slag and steel.

Elimination of Phosphorus and Sulphur. — The phosphorus is oxidized by the flame and ore to phosphoric acid, which in the

presence of the lime unites to form a phosphate of lime.   This
phosphate is practically stable under normal conditions, although
if the proper precautions are not observed, part of the phosphorus
may return to the bath.   While the removal of the phosphorus
may be complete before all the carbon is burned, most of the
manganese and all of the silicon will be oxidized before desul-
phurization can be finished.   The phosphorus exists in the slag
as a phosphate of iron and calcium.   The thermal conditions
accompanying oxidation of phosphorus favor its removal during
melting, as it enters the slag at a comparatively low temperature.
In good basic practice, the phosphorus is reduced to less than
0.04 per cent in the finished steel and not infrequently, in regular
practice, basic steel contains but from 0.01 to 0.02 per cent of
phosphorus.

Sulphur is a most difficult element to remove, and the results
obtained when efforts are made to remove it are irregular and
uncertain.   In good basic practice, about one-third of the sul-
phur in the charge is usually removed, although when manganese
and lime are added for this purpose, from 50 to 70 per cent of
the sulphur in the charge may be removed.

In the *Saniter* process, oxy-chloride of lime is used.   The
process requires the use of an exceedingly basic slag before the
oxy-chloride is added, as it is claimed that it is this excessive
basicity with the fluidity due to the oxy-chloride of lime that
enables the slag to absorb a larger amount of sulphur.

Adding the Recarburizers. — In the basic process, the recar-
burizers are added mostly in the ladle.   If manganese is added to
the bath in the furnace, it will come into contact with the slag
and reduce some of the calcium phosphate, thus rephosphorizing
the steel; in addition, much of the manganese would be lost
through oxidation.   In some plants that make very high-grade
steel, however, large lumps of manganese are thrown into the
bath, care being taken that the pieces are so heavy that they
pass right through the slag into the bath.   The manganese added
in this manner greatly improves the quality of the steel by
eliminating the oxides from the bath.   It is not uncommon in
the decarburized basic metal to have a high manganese content

either from the ore added to the bath or from the stock; this fact must be taken into consideration when recarburization is being made. Carbon recarburizers must always be added in the ladle, because if the carbon comes into contact with the slag, some of the phosphorus may return to the bath.

Basic-hearth Slag. — In the basic hearth, the slag must not only transmit heat and oxygen to the bath and protect the metal from oxidation, as in the acid furnace, but it must aid in the removal of the phosphorus and sulphur. For these reasons, more attention must be paid to this part of the bath than in the acid process. It is essential that the slag is basic both to remove the phosphorus and sulphur and to preserve the lining of the hearth. In addition, the slag must be fluid in order that it may flow freely in the furnace with, or immediately after, the steel, and that the reactions may take place easily. The lack of fluidity may check the oxidation of the metalloids by forming too great a restriction to the boiling.

Should the slag be very thin, watery, and black, burnt lime or limestone must be added, as the slag contains an excess of silica and iron oxide. With such a slag, the dephosphorizing has not been completed. As a rule, no more slag than is absolutely required must be formed, as it is a waste product. It usually ranges from 8 to 20 per cent of the charge.

Tilting Furnaces. — Because of the difficulty of tapping large furnaces, the tilting furnace· has been designed. Two types are in common use: One rotates on its axis, while the other is carried by a crane to the ladle or mold into which the metal is to be poured. In each case, the tap hole is located above the metal and slag line, so that a light tamping is sufficient; besides, all metal and slag are drawn off so that the bottom lasts longer and the back wall is easily patched. The acid furnace is lined with silica brick both on the sides and the roof. The basic hearth is lined with magnesite brick, which is carried far enough up the back wall so that the slag will not be in contact with the silica brick when the furnace charge is being poured. The use of these furnaces is especially advantageous in the basic process, as it is then possible to remove some of the slag and thus prevent

any phosphoric acid that has passed into the slag from returning to the metal. Other advantages of the tilting furnace are: Cold air is not admitted to the ports when the gas is shut off, because the port connections are broken; holes in the bottom are easily repaired; the furnace is easily tapped; and partly reduced metal is easily transferred from one furnace to another.

Most tilting furnaces are of the Talbot type, which are not removable but are rotated on their axes by hydraulic rams that cause them to move on rocker-like supports until the metal runs through the tap holes. These furnaces are strongly framed steel casings, approximately rectangular in section, inside of which a brick lining is built up. The curved rockers on their underside roll upon, and are supported by, strong steel braces. In case of accident, the furnace always returns by its own weight to its level position. The gas and air openings are enclosed in a cast-iron water-cooled ring which fits into a corresponding ring in the port when the furnace is upright. The ports are built inside a strongly framed steel structure that is mounted on four wheels. When the furnace is to be poured, each port is drawn back to avoid any friction between the ports and the furnace ends. The ends of the uptake from the regenerators are closed with cast-iron water troughs into which rings on the underside of the port openings project.

One of the special features of the tilting furnace is the "fore-hearth" which allows the steel to be poured directly into the molds without the use of a ladle. This forehearth is a brick-lined box-shaped casting that is provided with two pouring holes and stoppers. These holes are spaced the proper distance apart, so that, when the furnace is tilted, the metal flows into the hearth and then into both of the molds, which are carried by a small car, or "bogie." If it should be desired at any time, the forehearth may be removed and a spout substituted so that the steel may be run into a ladle as in ordinary practice.

Talbot Continuous Process. — In an effort to increase the output of the open-hearth furnace, special processes have been devised. The most important of these is that patented by Benjamin Talbot, in 1899. This process utilizes the tilting

furnace and is based upon the powerful oxidizing action of a slag rich in iron oxides. It consists in maintaining in the furnace a reservoir of metal by adding to the bath as much lime and pig iron as molten steel is withdrawn. Its chief advantages are: A larger output is obtained; the process is worked with pig iron and oxides or ores, so that the use of scrap is unnecessary; a greater yield is obtained from the metal charged; and pig iron high in silicon and phosphorus can be used. The increased yield of steel comes from the iron reduced from the oxides entering the bath. These oxides are rolled scrap, mill cinder, and ore. In order that the excess of slag formed may be removed, a hole is placed on the side of the furnace opposite to that on which the steel is tapped, and the furnace is arranged to tilt in this direction until the slag will run out. Large furnaces are used, hearths holding over 200 tons of metal not being uncommon.

At the beginning of each week, the furnace is charged and operated in the usual manner for open-hearth work. When the heat is completed, only from one-fourth to one-third of the bath is drawn off by tilting the furnace forward; this metal is recarburized in the ladle. The oxide of iron is then added to the bath and, after this is melted, as much hot metal and limestone is poured in as steel was tapped. A vigorous boiling action, like the Bessemer blowing, is at once caused by the discharge of large quantities of carbon monoxide. This gas burns with an intensely hot flame and generates sufficient heat to raise the temperature in the bath so that the producer gas is shut off from the furnace at this time. Within a few minutes, the slag is dissolved of its iron oxide so that a part of it is poured off; the bath is then reduced to steel of the desired quality by adding iron ore and lime. As soon as the steel is produced, a part of the bath is again poured off and the additions made as before. Sometimes the methods of adding the oxides, iron, and lime vary, a common practice being to add these in two or three lots and not all at one time. In this case, the amount added each time depends upon the violence of the reactions. Whatever method is used, the purification of the iron is quickly effected, if the slag is rich in oxides of iron and the percentage of impurities of the hot

metal added is considerably reduced by dilution with the purified metal in the furnace.

Monell Process. — The Monell process is much like the Talbot, but is carried out in a stationary furnace. It was worked out at the Carnegie Steel Co.'s works, and depends upon the strong oxidizing action of a slag rich in oxides of iron. The limestone and iron oxides are charged first, and when these are almost melted, molten pig iron is poured into the furnace. The entire heat is tapped when it is purified. The excess slag may be tapped off through a hole placed above the level of the metal, but its flow is not as easily controlled as when a tilting furnace is used; besides, the rich slag corrodes the bottom, thus necessitating careful attention to bottom repairs.

Bertrand-Thiel Process. — In the Bertrand-Thiel process, two furnaces are used, the metal being transferred from the "primary furnace," or "refiner," to the "secondary furnace," or "finisher." It was invented by Messrs. Bertrand and Thiel of Austria, in 1894, and may be worked with pig iron and ore, or pig iron and scrap, in whatever proportions may be desired. The furnaces are of the ordinary open-hearth type. The molten pig iron (or pig iron and scrap), ore, and limestone are charged into the primary furnace, and the resulting reaction removes all the silicon, most of the phosphorus and manganese, and part of the carbon. The metal is then run into the finisher, care being taken to prevent the transfer of any slag. Lime, ore, and, as a rule, scrap heated to the fusing point are here added to the bath. As the slag thus formed is rich in oxides of iron, the carbon and remaining phosphorus are quickly removed.

Duplex Process. — In the duplex process, both the Bessemer converter and the open-hearth furnace are used. This method is particularly applicable to the use of pig iron that is too high in silicon to be worked with advantage in the basic Bessemer or basic open-hearth process. The process consists in removing all the silicon and part of the manganese and carbon in an acid converter, and then decarburizing and dephosphorizing this metal in the basic open-hearth furnace. In the United States, the process is used mostly in the Southern fields where iron ore

suitable for this treatment is abundant. In 1916, 3,436,457 tons of steel ingots and castings were made by the duplex process.

Physical Characteristics of Open-hearth Steel. — According to the Manufacturers Standard Specifications for structural steel, as revised April 21, 1914, there are three classes of structural steel as previously mentioned in Chapter VII. Class A, which is used for railway bridges and ships; Class B, which is used for buildings, highway bridges, and similar structures; and Class C, which is used for structural rivets. Classes A and C must be made by the open-hearth process, while Class B may be made by either the open-hearth or the Bessemer process.

The physical properties required for Class A and B steel are as follows: Tensile strength, from 55,000 to 65,000 pounds per square inch; maximum yield-point, one-half of the tensile strength; percentage of elongation in eight inches equals a minimum of 1,400,000 ÷ tensile strength. The elongation in two inches should be a minimum of 22 per cent. Class B steel may have a tensile strength up to 70,000 pounds per square inch, provided the elongation is not less than the percentage required for 65,000 pounds per square inch tensile strength.

The physical properties of Class C steel are as follows: Tensile strength, from 46,000 to 56,000 pounds per square inch; maximum yield-point, one-half of the tensile strength; percentage of elongation in eight inches equals a minimum of 1,400,000 ÷ tensile strength. With regard to the chemical analysis, the following requirements are given:

Class A Steel. — The maximum phosphorus content, when made by the basic open-hearth process, is 0.04 per cent; when made by the acid open-hearth process, 0.06 per cent. The maximum sulphur content is 0.05 per cent.

Class B Steel. — The maximum phosphorus content, when made by the basic open-hearth process, is 0.06 per cent; and when made by the acid open-hearth process, 0.08 per cent. The sulphur content is not specified.

Class C Steel. — The maximum phosphorus content, when made by either the acid or the basic open-hearth process, is 0.04 per cent. The maximum sulphur content is 0.045 per cent.

CHAPTER IX

ELECTRIC STEEL

WHILE electric steel or steel made in the electric furnace is not a new product, the expansion of this branch of the steel industry has been very rapid, especially since 1914. In 1908 there was only one furnace in the United States producing electric steel and the output for the year was only about 55 tons. The number of electric furnaces operating in the United States on January 1, 1918, was 233 and many new installations have been made since that date. The estimated tonnage for electric steel during 1917 varies greatly, but according to several authorities one million tons or more were produced. Whatever the rate of production, it is certain that the electric steel industry, which a few years ago was in the experimental stage, is now on a firm commercial basis.

Early experiments in the production of electric steel were made by Sir William Siemens who constructed a small arc furnace in 1878. Twenty years elapsed, however, before the Stassano furnace, which was the first to operate commercially, was introduced. The use of electric furnaces would doubtless have increased more rapidly after the introduction of this process had it not been for the relatively high cost of generating electrical energy at that time. The wonderful advancement made in both the generation and distribution of electricity during recent years, combined with the advantages of the electric furnace for certain melting and refining processes, has resulted in the rapid development of this method of producing steel.

Application of Electric Furnaces to the Steel Industry.— Electric furnaces are adapted primarily for melting and refining processes, and they probably will never be able to compete with the blast furnace for smelting ore except under certain favorable conditions. What might be defined as an "electric blast fur-

nace" was developed in Sweden in 1910. This furnace is similar
in principle to an ordinary blast furnace, except that it is pro-
vided with three electrodes which take the place of the tuyeres.
The furnace operates without an air blast and either charcoal or
coke is used for melting the charge of iron ore. The charge is
fed into the top of the furnace in the usual way. The use of the
electric furnace for smelting iron ores is evidently limited to
localities where hydro-electric installations and cheap electrical
power are available. One electric furnace which has been in-
stalled in the United States and is used for smelting has a rec-
tangular steel shell lined with a refractory material and a sloping
bottom to facilitate the flow of the molten metal. Five stacks
which extend above the roof of the furnace are used for charg-
ing and graphite electrodes are located between these stacks.
The furnace is charged at regular intervals and its operation is
continuous.

The important applications of electric furnaces in the steel
industry are for making special alloy steels, tool steel (including
ordinary carbon steel and high-speed steel), for melting the steel
used in making steel castings, and for melting the ferro-alloys
which are added to "special steels" to secure different chemical
and physical properties. Most of the ferro-alloys used in the
United States prior to the war were imported, but at the present
time large quantities of the alloys used in producing high-speed
and special steels are manufactured in this country. These
alloys include ferrosilicon, ferrochrome, ferronickel, ferro-
tungsten, ferromanganese, ferrovanadium, etc. The electric
furnace has also been used to a limited extent for refining cupola
iron preparatory to making malleable castings.

Most of the electric steel produced is used either for making
special alloy steels or tool steel, although the electric furnace is
used extensively in steel foundries. No accurate data is avail-
able as to the amount of tool steel made electrically as compared
with the output of the crucible process. Some steel-makers and
metallurgists contend that the electric furnace not only produces
much more tool steel at the present time than the crucible process,
but that ultimately it will be used almost exclusively for tool

steel production. Others connected with the steel industry believe that there will continue to be a field for both the electric and crucible processes and that the electric furnace is adapted more especially for the production of special alloy steels for use in the construction of automobiles, airplanes, ordnance, etc. Steel may be produced in the electric furnace which is undoubtedly equal to crucible steel in quality if not superior to it, and it is claimed that the electric process is more economical, especially at the present time, on account of the cost of crucibles. There is a decided difference of opinion regarding the present and future use of the electric furnace in preference to the open-hearth furnace. Even though the cost of electric steel is higher than open-hearth steel, the greater degree of refinement and closer regulation that is possible with the electric furnace offset this difference of cost for the finer grades of steel. In steel foundry practice, it is claimed that an equivalent tonnage of high-grade electric steel can be produced at an average lower cost than the ordinary commercial grades of open-hearth steel, since the charge of the electric furnace may consist entirely of old scrap which is cheaper than the combined scrap and pig iron required with the other process. One of the striking features of the electric furnace development is in regard to the size of the installations. A great many plants are now equipped with furnaces having a capacity of five or six tons, but ten, fifteen, and twenty-five ton sizes are in use. The United States now leads in the number of electric furnaces in operation and Great Britain occupies second place. The world's largest single center of electric steel production, however, is in Sheffield, England.

General Classes of Electric Furnaces. — Electric furnaces are used either for melting and refining metals, or for heating them to some temperature below the melting point, as in connection with the heat-treatment of steel. The three general types in use may be classified electrically as arc furnaces, resistance furnaces, and induction furnaces. With each type, the heat is derived from electrical resistance, but the nature or form of the resistance varies in the different general classes of furnaces mentioned. The arc furnace, which is the most important

type in the steel industry is equipped with electrodes, the current passing from one electrode to another. These furnaces differ in regard to the arrangement and number of the electrodes, as explained later. The arc furnace is used almost exclusively in the production of electric steel.

While all electrical furnaces depend upon electrical resistance, the general type in which heat is generated by the passage of a current either through the charge or through a resistor forming part of the furnace is classified as a resistance type to distinguish it from the others. Some of these resistance furnaces are so arranged that electrodes come into contact with the charge and the latter forms the resistance. This is the direct resistance class. Another type has a resistor which surrounds the furnace crucible and heats it by direct radiation, and there is a third class in which the heat generated in the graphitic or other resistor is radiated to the walls of the furnace and is then reflected onto the charge. Resistance furnaces in general are used principally for heat-treating, annealing, and for melting nonferrous metals.

With the induction type of furnace, the heat is generated in the metallic charge by means of induced currents. This type is similar in principle to a static transformer, the material heated corresponding to the low tension winding. Thus, the induction furnace may be defined as an electrical apparatus which contains within itself the transformer that induces the heat in the charge, whereas the arc furnace is practically a hearth which holds the charge, and the arc is the source of heat and serves the same purpose as the flame in an open-hearth furnace. The first induction furnace for steel melting was developed by Kjellin, in Sweden, about 1900. The primary winding of a Kjellin type surrounds the core and is within a cylinder made of refractory material and cooled either by circulating water or a forced draft. The annular shaped hearth containing molten metal is beyond the windings and acts as a single turn of the secondary winding; consequently, when current flows through the primary winding, a current is induced in the bath of metal which is thereby heated, practically all of the electrical energy being converted into heat. Induction furnaces are used very

little in steel plants, but are applied principally in melting non-ferrous metals.

Methods of Operating Electric Furnaces. — Electric furnaces may either melt a cold charge or they may receive the metal in a molten condition. Most of the electric furnaces now in use are for cold melting, but the larger sizes are commonly arranged to use molten charges. After the introduction of the electric furnace, steel manufacturers soon recognized that it might be used to advantage in conjunction with the Bessemer converter and open-hearth furnace, following the plan of the well-known "duplex process" by which the metal is partly purified in a Bessemer converter and is then further refined in the open-hearth furnace. In fact, the first electric furnace installation in the United States consisted of an open-hearth furnace for preliminary melting and refining, and an electric furnace which received the molten metal for deoxidizing and desulphurizing it and for making whatever additions or changes might be necessary to secure the desired analysis. This is often called the "hot metal process." Both Bessemer converters and open-hearth furnaces are also used in conjunction with the electric furnace. The Bessemer converter is used for decarbonizing and desiliconizing the metal; the open-hearth furnace is then used for dephosphorizing it, and the refining process is then completed by deoxidizing and desulphurizing in the electric furnace. One installation operating on the triplex system consists of ten electric furnaces having a nominal capacity of 25 tons each, two 25-ton open-hearth furnaces, and two 25-ton Bessemer converters, the three processes being used in tandem. The metal is first "blown" in the Bessemer converter. Then it is transferred to the open-hearth furnaces and finally to the electric furnaces. The estimated capacity of this plant is 50,000 tons of electric furnace steel per month.

Electric furnaces may either be basic or acid, but a large percentage are lined for basic operation. The basic furnace permits the use of a basic slag which serves to remove impurities from the metal, just as in the basic open-hearth furnace. Thus phosphorus, sulphur, and oxygen may be removed, which per-

mits using relatively cheap raw materials.   With the acid process, no phosphorus or sulphur is removed, and if these elements are to be held within narrow limits, the materials composing the charge must be carefully selected.

Advantages of the Electric Process. — The steel produced in the electric furnace may be chemically purer than that made by any other process, although it does not necessarily follow that electric steel has superior physical qualities simply because it is pure chemically.   Inferior grades of steel may be produced in the electric furnace, and the extremely high temperatures obtained from the electric arc are often referred to as the principal cause of poor electric steel.   The fact remains, however, that the electric furnace when properly designed and used is capable of producing steel which chemically or physically is unexcelled. One advantage of the electric furnaces is that they permit of closer control of the composition of steel than any other process, which accounts for their use for instance in preference to the open-hearth furnace in the production of special alloy steels. In the electric furnace, since the heat is obtained from the electric current and no fuel is burned, there are no impurities introduced from the gases of combustion; in fact, fusion may be effected in a neutral or reducing atmosphere.   Less excess alloy needs to be added to the heat in an electric furnace to insure the proper amount in the finished steel.   Some steel-makers claim that it is necessary to use only one-half the amount of ferromanganese that would be required with the best open-hearth practice.   Another point in favor of the electric furnace is that the alloy additions for making alloy steels may be made in the furnace itself, rather than in the ladle, thus insuring thorough assimilation, diffusion, and a more homogeneous product.

Accurate control of the composition of electric steel tends to make the results of heat-treatment more certain, and it may be subjected to a higher degree of heat without injury in forging or in connection with heat-treatment than is the case with other steels.   The electric furnace also has an advantage in that it may be used in recovering alloy scrap, which, in some cases, is not

desirable to include in the charge of an open-hearth furnace. Furthermore, when alloy scrap is used in an open-hearth furnace, a large proportion of the alloy metal is lost in the slag. It is practicable to use relatively cheap raw materials in the electric furnace and to convert them into high-grade steel, which can be deoxidized and desulphurized almost completely. The phosphorus and sulphur may not exceed 0.010 per cent, and in carbon steel the average sulphur content is lower, whereas, in alloy steels, the sulphur barely exceeds 0.015 per cent.

Tests of electric and open-hearth steels each having a carbon content of 0.12 per cent showed the following physical properties: Ultimate strength of open-hearth steel, 56,500 pounds per square inch; elongation in two inches, 29.82 per cent; ultimate strength of electric steel, 65,200 pounds per square inch; elongation in two inches, 26.05 per cent. When the carbon content was increased in each case to 0.20 per cent, the ultimate strength of the open-hearth steel was 58,320 pounds per square inch; and the elongation in two inches, 28.35 per cent. The ultimate strength of the electric steel was 73,150 pounds per square inch, and the elongation in two inches, 22.75 per cent.

Types of Arc Furnaces Used in the Steel Industry. — Since the arc furnace is used almost exclusively in the steel industry, only this general type will be considered. All arc furnaces may be divided into two classes, first, the arc radiation class and, second, the arc resistance or arc conduction class. Furnaces of the second class may belong either to the short arc type or the long arc type. The Stassano furnace, which was the first commercial design, heated the metal almost entirely by radiation from the electric arc and it belongs to the arc radiation class. The arc resistance type is so arranged that heat is generated by the arc and by the passage of current through the charge. The current may either pass along the surface of the charge to the other electrodes or through the body of the charge.

The arc furnace may use either direct or alternating current, the latter being used largely since this is the current supplied by most power companies. The three-phase current is employed more than the two-phase or single-phase. The voltage depends

upon the length of the arc, as the latter is a form of electrical resistance.   Whatever voltage is required for melting or heating is obtained by transformers at the furnace, so that the transmission voltage may be of any value.

Héroult Electric Furnace. — The Héroult furnace, which is now used more than any other type, belongs to the arc resistance class.   The electrodes are placed above the bath and the cur-
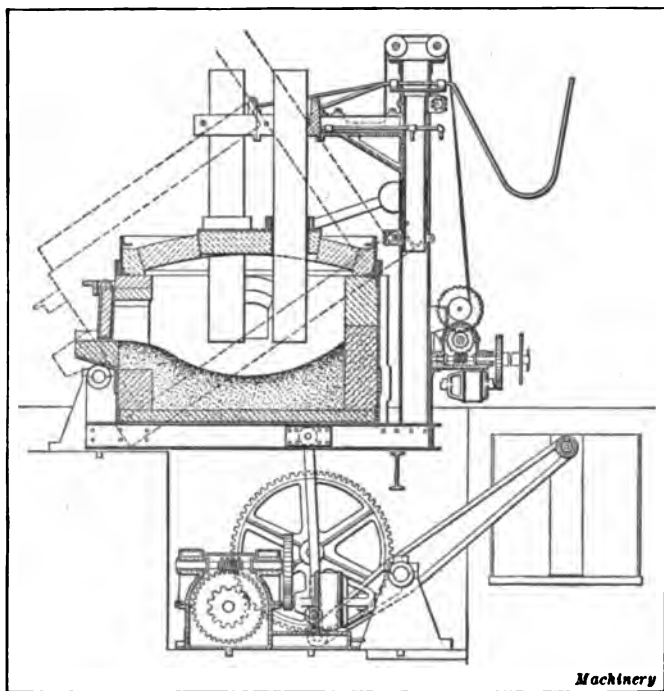
Fig. 1.   Small Héroult Furnace and its Electrically-operated
Tilting Mechanism

rent passes from one electrode to the metal and from the metal to the next electrode.   In this way, the bath is heated both by the heat radiated from the arc and by the heat produced by the resistance of the steel and the slag to the passage of the current through them.   Fig. 1 shows a sectional view of a three-phase Héroult furnace and its electrically-operated tilting mechanism. The three electrodes extend down through the roof of the fur-

nace and are so located that lines joining their centers would form a triangle. The steel shell of the furnace is lined with a refractory material, the exact nature of which depends upon whether the furnace is to be basic or acid in its operation. The three electrodes are connected with the transformers by flexible cables which permit the furnace to be tilted while pouring the charge. The furnace shown in Fig. 1 is so arranged that it tilts about a hinge located just below the spout so that the latter remains nearly stationary while pouring. The dotted lines in-

Fig. 2.   Twenty-five ton Héroult Furnace receiving Charge of Molten Metal

dicate the pouring position. Power for tilting the furnace is derived from a motor which transmits motion to a large gear wheel through a combination of spur and worm gearing. This gear wheel is connected directly with the furnace by means of rods, as the illustration shows. One advantage of this arrangement is that, if the operator fails to stop the motor, the furnace will simply descend to its original position; moreover, when the furnace is either at the upper or lower positions of the stroke, it will move in the desired direction, no matter which way the

controller is operated.   The weight of the furnace is balanced by a counterweight which connects by means of levers.

The 25-ton Héroult furnace illustrated in Figs. 2 and 3 is the largest size in use at the present time.   Fig. 2 shows a charge of molten metal being poured from the ladle into the furnace, and Fig. 3 shows the furnace tilted and the refined charge being poured.

Snyder Electric Furnace. — The Snyder electric furnace belongs to the arc resistance class and is a long arc type.   The
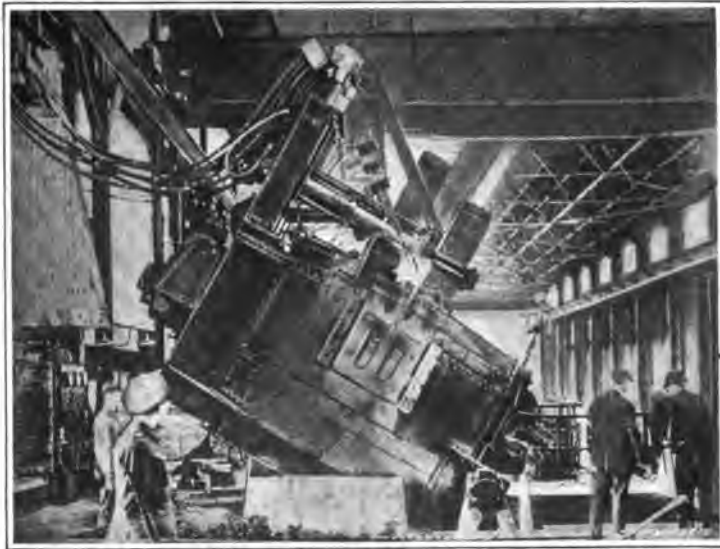
Fig. 3.   Twenty-five-ton Héroult Furnace in Pouring Position

electric current may be either single-phase, two- or three-phase, or direct-current, but the latter is not commonly used.   The single-phase or direct-current furnaces have two electrical connections, whereas the two- or three-phase furnaces have three or more, according to the type.   The three-phase furnace has two of the phases connected to the movable carbon electrodes at the top, while the third is connected to a metal contact at the bottom of the furnace.   The Snyder furnace is doorless, and the entire roof of the furnace is tilted back for charging, as shown by the illustration, Fig. 4.   After the charge has been dropped into

the furnace, the roof is pulled forward by a motor and sealed with a dry fireclay gasket. The electrodes may be either hand or motor operated, an automatic regulator being applied in the case of motor operation. An advantage claimed for the long arc is that it minimizes the necessity of moving the electrodes. The opening roof feature also reduces the time for charging, since
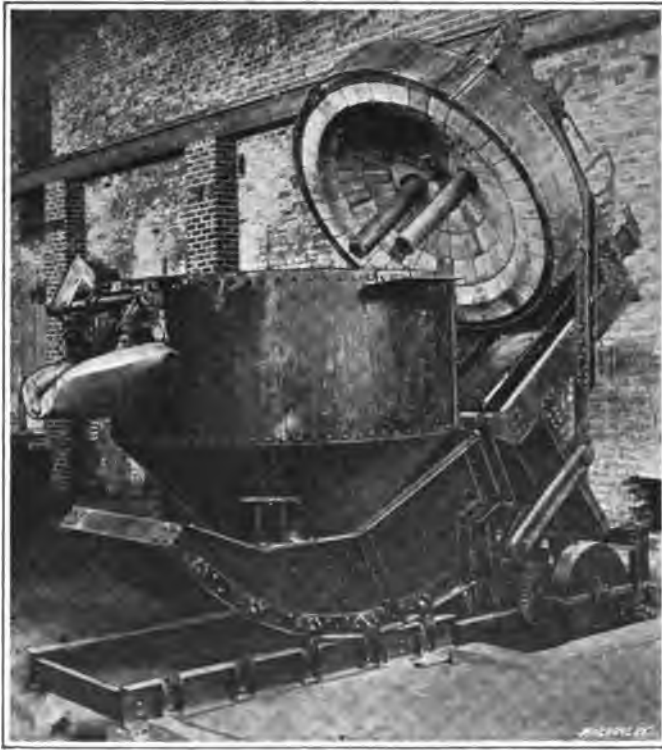
Fig. 4.   Five-ton Snyder Furnace with Roof tilted back for Charging

machinery can be used instead of shovels. These furnaces are arranged in three different ways to meet the pouring requirements under different conditions. With the rocking type, which is illustrated in Fig. 4 and is the most common, the end of the spout moves forward and down as the furnace is tilted to the pouring position. This type is recommended when it is relatively easy to move the ladle to correspond with the movement

of the spout. The second or "heaving" type has a circular shaped rocker underneath the furnace which is so located that the spout remains practically stationary as the furnace is tilted. This arrangement is especially adapted for hand ladle work. With the third or "dumping" type, the spout moves down and backward. This type is ordinarily preferred for small installations in which it is easy to follow the spout with hand ladles.
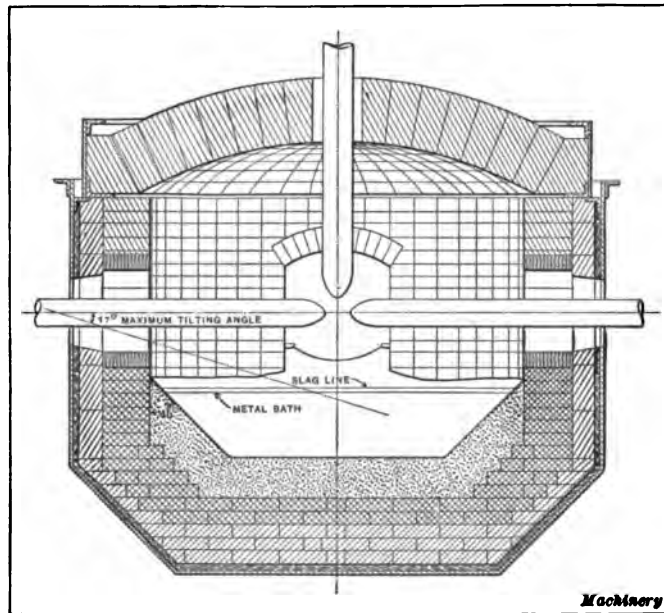
Fig. 5.   Sectional View illustrating Arrangement of Electrodes
in Rennerfelt Furnace

Rennerfelt Electric Furnace. — The Rennerfelt electric furnace operates with a free burning arc like the Stassano furnace, but differs from the latter in the way the arc is formed. A cross-sectional view of a three gross-ton size is shown in Fig. 5. There are three electrodes, a vertical electrode being placed between two electrodes which are shown in a horizontal position, but may be tilted, as explained later. The vertical electrode carries about 40 per cent more current than the others, so that the arc is thrown downward toward the bath and away from the

roof of the furnace. The three-phase current, which may be of any voltage and frequency, is transformed to a two-phase three-wire system. The two side electrodes are connected to the terminal of each phase, and the top electrode is connected to the middle conductor. The power input is regulated by moving the side electrodes in or out, thus changing the length of the arc. This adjustment may be effected by hand or by electric motors controlled either automatically or by means of push-buttons. The top electrode has to be moved downward perhaps once an
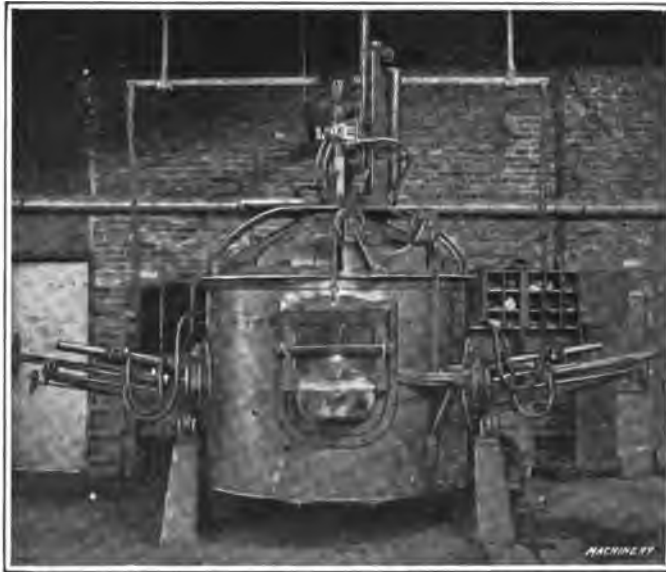
Fig. 6. Front View of One-ton Rennerfelt Furnace

hour, depending upon its consumption. When charging the furnace, the side electrodes are tilted upwards, thus leaving sufficient space beneath for inserting the whole charge at one time. As the charge melts, the electrode ends are continually lowered, thus keeping the flame about two or three inches over the bath. A one-ton Rennerfelt furnace is shown in Fig. 6. The electrodes at the sides and their holders, and the upper vertical electrode, may be seen in this illustration. These furnaces are provided with trunnions resting on roller bearings supported

by frames at the sides and they are tilted either by hand or by motors, depending upon the size. The furnaces with a capacity up to one ton have only one working door which is used both for charging and pouring; the larger furnaces have one charging and one pouring door.

Booth-Hall Electric Furnace. — The Booth-Hall furnace (see Fig. 7) is so arranged that power is introduced through one, two,

Fig. 7. Booth-Hall Furnace of Four-ton Capacity

or three main vertical electrodes, the number depending upon whether the furnace is to operate single-phase, two-phase, or three-phase. The furnace also has an auxiliary electrode and wrought-iron grids which are imbedded in a hearth with a re-fractory facing. The auxiliary electrode is inserted vertically through the roof, except in small furnaces, in which case it is inserted obliquely through the door opening. The two-phase

furnace is considered preferable for the usual power supply and steel refining conditions, and the following description applies particularly to this class:

When starting a heat in a two-phase furnace with a cold charge, a pawl on the auxiliary electrode holder is released, permitting the electrode to rest upon the scrap charge. Arcs are then drawn with the two main electrodes and the metal begins to melt under these arcs. The auxiliary electrode acts as a common neutral or return, no arc being drawn, and consequently no melting occurs under the auxiliary electrode. When enough molten metal has accumulated on the hearth to make the latter a conductor of electricity, the current begins to flow through the wrought-iron grids. The auxiliary electrode is then withdrawn from the furnace entirely, and the opening for it is closed. The furnace then continues to operate, the current passing through the main vertical electrode, the bath, and the hearth, and out through the grids. The transformer connections are so arranged that each of the two phases has an independent circuit. The arcs are governed by automatic electrode regulators for maintaining a uniform power input into the furnace and a balanced load on the lines.

Since there are only two electrodes entering the roof of a two-phase furnace except at the beginning of a heat, it is claimed that the furnace has a relatively low radiation loss, less electrode breakage and electrode consumption, as well as a lower initial cost for the furnace equipment, as compared with types having three or four main electrodes. The possibility of failure to secure contact when starting a heat is said to be eliminated by the use of the auxiliary electrode. The two main electrodes and the auxiliary electrode acting as a common neutral makes it possible to use the arcs for sintering in the hearth of the furnace layer by layer, thus forming a monolithic mass that is durable. All the tilting and electrode regulating mechanism is below the floor and is completely covered. Furnaces ranging from 2½ to 6 tons capacity are built two-phase, since in practically all localities a single-phase load for such furnaces would not be acceptable to power companies. For refining steel, the two-phase

furnace is recommended, except in 8 and 10 ton sizes, in which case the three-phase type is regarded as more practicable. Furnaces up to 1½ ton holding capacity intended for the straight melting of scrap are made single-phase, unless power conditions are such that a single-phase load is not acceptable.

Ludlum Electric Furnace. — The Ludlum electric furnace is an ellipsoidal form and it has three electrodes which extend down

Fig. 8. Ten-ton Ludlum Furnace in Pouring Position

through the roof. These electrodes instead of being located in triangular formation are in a straight line corresponding to the center line of the furnace (see Fig. 8 which shows a 10-ton furnace in the pouring position). The electrodes are held by bronze arms projecting from upright beams attached to the furnace structure. These arms may be raised and lowered by the automatic control or by handwheels. There are no bottom

connections. The shape of the furnace is such that there are no straight side walls nor over-hanging walls with the furnace in any working position. There is a door at each end of the furnace but no spout. The furnace can be charged from both ends at once, and it is tilted by an electric motor to pour through one of the doors.
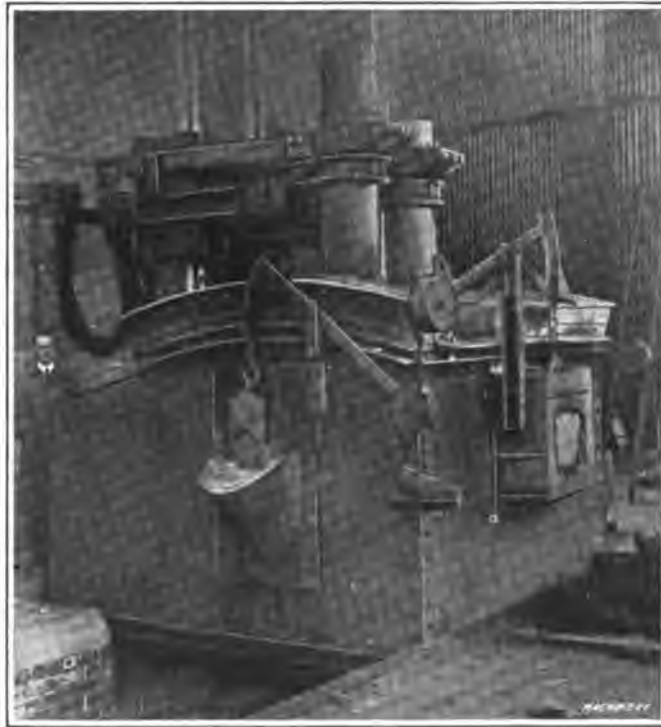
Fig. 9. Three-ton Greaves-Etchells Furnace

The furnace is filled with the charge of scrap to be melted, and at first the electrodes rest on the charge so that soon after the current is turned on the electrodes melt their way through nearly to the bottom. By this time, a pool of molten metal has formed beneath the electrodes because the deepest part of the hearth is directly below them. The charge is melted from the bottom up, the arcs remaining covered by the scrap until the latter is completely melted, so that the roof is not exposed to

the high temperature radiating from an open arc. The roof of this furnace is in the form of a low arch and, in practice, an extra roof is built on a separate frame, so that the old one can readily be replaced at any time. For basic operation, the hearth is lined with magnesite brick to a thickness of 9 inches or more.

Greaves-Etchells Electric Furnace. — The Greaves-Etchells furnace has two of the phases connected to the two electrodes above the bath while the third phase is connected to a copper
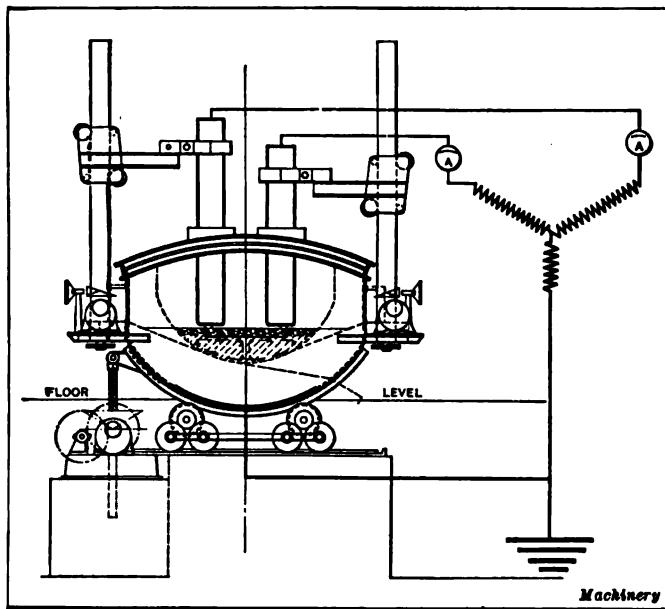
Fig. 10. Diagram illustrating Arrangement of Twelve-ton
Greaves-Etchells Furnace

plate which extends over the bottom of the furnace. (See Fig. 9 and also the diagram, Fig. 10.) The current flowing through the hearth generates considerable heat below the bath and the electric arcs above the charge maintain the slag and surface at the desired temperature. Convection currents in the metal, resulting from the bottom heating, cause a continuous circulation of the metal and uniform heating. The hearth lining, which is at least 20 inches thick, is made of dolomite, magnesite, and other materials, in such a way that the electrical resistance is high at

the inside of the bath in proximity to the charge and decreases rapidly to a negligible quantity at the outside. The system of transformer ratios is arranged to give a balanced condition when the upper electrodes are in equal adjustment. The equipment has been designed to withstand any short-circuiting of the electrodes which may occur during the melting process when pieces of scrap fall against the electrodes. The transformer connections are such that the short-circuit current of one electrode must traverse two transformers in series and in different phase which automatically lowers the power factor momentarily and has a strong buffer effect; moreover, the permanent resistance in the path of the current through the hearth also limits the effect of short circuits. The raising or lowering of the electrode for regulating the energy supplied by the furnace may be effected by automatic regulators or by hand control. The voltages across the arcs may also be varied in all except the smallest

Fig. 11.   Diagram showing Arrangement of Electrodes in Girod Furnace

size of furnace, and the ratio of heat generated above and below the bath may be regulated over a wide range. The tilting mechanism is so arranged that the spout travels downwards in a vertical line when pouring.

Girod Electric Furnace. — The Girod electric furnace is an arc conduction type of the class having bottom connections. The current is supplied by one or more carbon electrodes A (see Fig. 11) which extend down through the furnace roof. The lower ends of these electrodes are near the level of the slag as in other furnaces. In the bottom of the furnace and as far as possible from the upper carbon electrodes, there are six or more steel electrodes B which pass through the refractory bottom and

are in direct connection with the furnace shell and the low-tension side of the power plant. With this arrangement, the current is forced to pass through the charge, the object being to obtain a more uniform heat than when the arc is formed above the charge or passes through the upper surface. Another advantage claimed for the Girod furnace is that the current passing through the bath produces an electromagnetic field which gives the bath a rotary movement and accelerates chemical reaction.

The Girod furnace may be adapted to any system of current, and the usual tension is 65 volts for small furnaces and 70 volts for large ones. The use of single-phase alternating current is considered preferable for furnaces of small capacity. Furnaces up to four tons in capacity are generally single-phase and have one carbon electrode, whereas larger sizes are three-phase and have three carbon electrodes. The use of a single-phase furnace involves, in a three-phase distribution system, the installation of rotary converters or motor generators with transformation losses of about 14 per cent. The three-phase furnace simply requires step-down transformers with energy losses of only 3 or 4 per cent. The connections of a three-phase furnace are arranged to give an equal load on each phase. The furnace is fitted with a sliding door through which the charge is inserted and the slag removed. Opposite the door is the tap hole.

Electrodes for Electric Furnaces and Their Regulation. — The electrodes used in electric furnaces for steel melting and refining are made either of amorphous or graphitic carbon. The graphite electrodes are generally used on the long arc type of furnace, but many short arc furnaces are provided with amorphous carbon electrodes, because of the "umbrella" effect, since they are twice as large in diameter as the graphite electrodes and afford better protection for the roof against the intense heat radiated directly from the arc. While the electric conductivity of graphite is much higher than that of amorphous carbon, the former is more expensive. The number of electrodes depends upon the kind of current used and whether or not there are electrical connections through the bottom of the furnace. With bottom connections, a single-phase furnace requires one elec-

trode; a two-phase furnace, two electrodes; and a three-phase furnace, three electrodes. If there are no bottom connections and the current either passes from one electrode to the other through the bath or is arranged to maintain the arc above and clear of the bath, then a single-phase furnace requires two electrodes; a two-phase furnace, four electrodes; and a three-phase furnace, three electrodes.

The adjustment of the electrodes to regulate the length of arc and the flow of the current may be effected by hand, but an automatic regulating device is generally employed. Hand regulation involves constant attention on the part of the operator, and is laborious on the large furnaces so that automatic regulation is preferable. The Thury system of regulation, as applied to a three-phase furnace, has three regulators, there being one for each electrode. The electrodes are maintained in the desired positions by means of these regulators in conjunction with the motor-driven electrode adjusting mechanism. The regulators are connected to a motor-driven countershaft, and each regulator is in the form of a double-throw switch for rotating the motor in either direction. The operation of this switch is controlled by a solenoid which is energized by current from a series transformer in the main circuit on the high-tension side. The regulating mechanism controlling the switch is held in equilibrium when the flow of the current is normal. Any decided variation in the flow causes the regulator switch to be thrown in whatever direction is required to restore the normal current flow by adjusting the electrodes. The electrode holders should be water-cooled in order to prevent arcing at the connections, although this may not be necessary on very small furnaces.

The automatic electrode control made by the General Electric Co. has a control panel consisting of three sections. On the upper section are located three electrode groups, each consisting of one contactor group and one shunt relay. This shunt relay is connected across the alternating-current circuit and if the latter is broken or the power fails for any reason, the relay opens the control circuits, thus preventing damage to the furnace and loss of heat. The contactor group consists of one raising

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contactor, one lowering contactor, and one dynamic breaking
contactor, all mechanically interlocked. On the middle section
of the panel there is a glass case containing three contact-making
ammeters, each controlling one contactor. Below each ammeter
there is a dial switch for varying the number of effective turns
in the ammeter coil and in this way the amount of power fed
to the furnace. (A more recent design is equipped with a
rheostat in shunt with the ammeter coil.) On the bottom sec-
tion of the panel, there are four double-pole single-throw switches.
One of these is a totalizing switch for the electrode motors, each
motor being controlled by one of the three additional switches.
On the back of the panel, three contactors are located for
varying the resistance in series with the electrode motors when
changing from normal to the emergency conditions, and *vice
versa.*

Electric Furnace Linings. — Magnesite and silica are the prin-
cipal materials used for electric furnace linings. In a basic
furnace, the lining of the hearth and up to a point a little above
the slag line is usually of magnesite, although dolomite may
also be used. The furnace wall above the slag line may be lined
with silica, magnesia, or chrome brick, the material being se-
lected according to conditions. Silica is used for the roof lining
of a basic furnace, and an acid furnace is lined with silica through-
out.

The Rennerfelt furnace illustrated in Fig. 5 is lined for basic
operation. Firebrick is placed next to the shell as indicated
by the single section lines. The next layer, which extends
slightly above the slag line, consists of magnesite bricks (in-
dicated by cross-hatching or double section lines) and an inner
fused lining of dead burned magnesite. The side walls from the
point where the magnesite bricks end, up to the roof, are lined
with silica bricks which are also used for the roof. For acid
operation, the bottom of the furnace would be made up of silica
bricks with a fused lining of ganister on top, and the walls and
roof would be lined with silica brick.

Electric Furnace Current Consumption. — The current con-
sumed by an electric furnace per ton of metal refined or melted

depends somewhat upon the kind of steel, the degree of refining, the size of the furnace, and the general operating conditions. A furnace melting and refining plain carbon steel may have a current consumption as low as 450 kilowatt-hours per net ton, whereas, in the case of alloy steels, the consumption may vary from 600 to 800 kilowatt-hours. The current consumption is usually larger for the smaller installations and may be 800 or 900 kilowatt-hours for a furnace operating on special steels. When the sulphur and phosphorus contents with a given grade of scrap must be reduced to very low limits, more power is required, because more slag, made principally of lime, must be melted. Electric furnaces melting cold scrap and converting it into tool or alloy steels (using two slags) ordinarily have a current consumption varying from 700 to 800 kilowatt-hours per net ton, whereas, when producing a merchant grade of carbon steel (using one slag), the consumption may not exceed from 500 to 650 kilowatt-hours per ton, the amount depending upon the size of the furnace, the rapidity of the melting, and the grade of the scrap, rusty deoxidized scrap requiring more power. When the charge is not melted in the electric furnace and the latter is used in conjunction with either the Bessemer converter or the open-hearth furnace, the current consumption is relatively low. For instance, furnaces operating on the triplex system have required only 110 kilowatt-hours per ton.

CHAPTER X

ROLLING AND DRAWING BARS, RAILS, PLATES, SHAFT-ING, AND WIRE

THE ingots cast into molds from the molten steel made by
any of the different processes described in the preceding chapters
are transformed into bars or sheets by means of rolling in a
rolling mill. The term "rolling mill" is applied both to the
machine in which the rolling is performed and to the plant
where the rolling operations are conducted. A rolling mill
plant is generally so arranged that the raw material enters at
one end and the finished material leaves at the other. The
rolling mill, in its narrower sense, may be defined as a machine
used for producing bars of uniform cross-section, as well as flat
sheets or plates, by passing a short heavy piece of material, such
as a "bloom" or "billet," between rolls which gradually reduce
it to the required form. Final finish may also be given to bars
by drawing them through dies, which operation is known as
"cold drawing" or "cold rolling," the latter term being incor-
rect in that the operation is not a rolling operation. Wire is
produced from rolled rods by drawing them through dies by an
operation known as "wire drawing."

 The earliest rolling mills were used in England in the latter
part of the eighteenth century; they were provided with plain
grooved rolls for making round bars. Angles and T-iron were
later rolled, and, in 1820, the first rail was produced by rolling
in England. Later, the practicability of rolling plates in a roll-
ing mill was recognized, the first plate mill being built in Ger-
many. The first I-beams and channels were rolled in France,
and the first segmental shapes used in older designs of built-up
columns were rolled in the United States. Thus, each of the
large industrial nations contributed its share to the development
of the rolling mill process which has been one of the most impor-

tant of the methods used in connection with the iron and steel
industry, and which has made possible the enormous develop-
ment of the use of iron and steel for structural purposes.

The Rolling Mill. — A rolling mill consists primarily of two
or more cast-iron or steel cylinders set one directly above the
other in a frame or housing, so that their axes are parallel. The
rolls are provided with a drive so that they will rotate in opposite
directions. Rolling mills may be either "two-high" or "three-
high," depending upon whether two or three rolls are mounted
one above the other. In
the two-high mill, the ar-
rangement of the rolls
being shown diagramma-
tically at *A*, in Fig. 1, the
bar can be passed through
the rolls in one direction
only, and is then passed
back to the front of the
rolling mill by being passed
over the top roll, as indi-
cated by the arrow marked
"return." In the three-
high type, the rolls are so
arranged that the bar will pass between rolls both on its forward
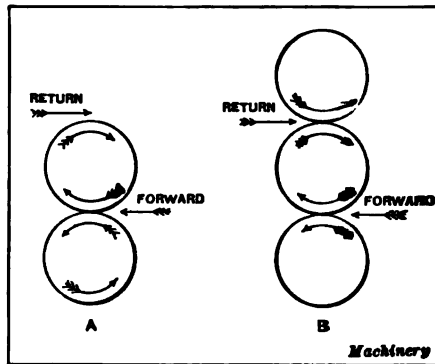
Fig. 1. Arrangement of Rolls on a
"Two-high" and a "Three-high"
Rolling Mill

and return passage, as indicated at *B*, in Fig. 1. It is evident
that, in the two-high rolls, the return passage of the bar is an idle
pass, involving a loss of time. In order to avoid this idle pass,
two-high rolls are often made reversing, in which case, as soon
as the bar has passed through the rolls in one direction, the rota-
tion of the roll is reversed and the bar is passed through in the
opposite direction. The reversal is controlled either by a clutch
and gearing or by reversing the mill engine. In the two-high
non-reversing mill, all the impurities are worked toward one
end of the bar, because the metal passes through the mill in the
same direction at every pass; but in the two-high reversing and
in the three-high mills, the impurities are worked toward the
center of the bar, as the bar is rolled from each end. There

is an advantage in having the impurities all worked toward one end of the bar, as in the two-high non-reversing mill, because then that end of the bar can be cut off and a better product is obtained. The greatest objection to the three-high mills, however, is that the work must be raised on one side and lowered on the other to make it enter the proper grooves; in the case of heavy work this necessitates the use of mechanical devices. The reversing two-high mills eliminate these raising devices; but the motors and engines required for driving these mills are so large and powerful that they are expensive to install; they are, therefore, used only in plants rolling work that is difficult to raise and handle.

In the early days, only two-high mills were used, but, in order to save the idle time required for passing the bar back over the top roll, and also in order to prevent the cooling of the metal which was due to this idle pass, the three-high mill was designed. As work is done on the metal at all times, it does not have time to cool off between passes, and the output of the plant is greatly increased.

Each set of rolls is arranged in a housing known as a "stand." The centers of the rolls of each stand are maintained the proper distance apart to effect a definite reduction in the thickness of the metal passed between them. This change in thickness is, of course, accompanied by a corresponding increase in the length of the bar being rolled.

As a rule, the rolls are arranged in "trains." These are formed by placing two or more stands in a row, and driving all of the rolls by one engine or electric motor. The engine or motor drives the train through gears which are connected to the rolls by "breaking pieces"; similar pieces also connect the rolls of adjacent stands. These "breaking pieces" are spindles that are just strong enough to transmit the maximum power required to drive the rolls. As a result, should a plate or bar stick while passing through the rolls these pieces will break and thus protect the more costly rolls from damage. These breaking pieces are connected to the rolls and the gears by sleeves that slip over the shaped ends of the rolls, so that the connection may be quickly made or broken.

The Rolls. — The rolls are either cast-iron or steel cylinders, provided with grooves for gradually reducing a heated ingot, billet, or bloom to the cross-sectional shape required. When flat sheets or plates are to be rolled, plain cylindrical rolls are employed. The rolls, when made from cast iron, may be either *grain* rolls or *chilled* rolls. Grain rolls are made from a tough grade of cast iron, and are used for roughing-down rolls. Chilled rolls are made from mottled iron cast in cast-iron molds, which chill the surface, making it very hard. These rolls are used for finishing. Rolls made from steel castings are now often used for heavy work. They are more expensive than cast-iron rolls, but are more durable and may be made lighter for equal strength. They are especially used in armor-plate rolling mills. The total length of the roll should not exceed about four times its diameter, as it otherwise is liable to spring. The rolls vary in size from 6 inches in diameter, for those used for rolling small sizes of bars, to 50 inches in diameter, for those used in making armor plate.

Definitions of Rolling Mill Terms. — A " bloom " is a square unfinished piece of steel which is about 6 inches square or larger. A "billet" is a square or round section of steel which may be from $1\frac{1}{2}$ inch in diameter or square up to about 6 inches in diameter or square. A "slab" is a flat piece of steel at least 2 inches thick and 12 inches wide. A "sheet bar" is a flat piece that is less than 2 inches thick, but from 6 to 12 inches wide. By rolling down blooms, billets, slabs, and sheet bars, bars, rods, bands, and hoops are obtained. These have great length compared with their width and thickness. A *bar* may be square, round, or flat (rectangular) in section. Round and square bars are rolled in sizes of from $\frac{1}{16}$ to $7\frac{1}{4}$ inches, the sizes from $\frac{3}{4}$ to $3\frac{1}{16}$ inches being standard. *Flat bars* or *flats* are commercially rolled in sizes of from $\frac{3}{4}$ inch wide by $\frac{1}{4}$ inch thick up to 6 inches wide by 4 inches thick. Flat bars in sizes from $\frac{3}{4}$ inch wide by $\frac{1}{8}$ inch thick to 6 inches wide by $\frac{1}{16}$ inch thick are classified as "light" bars, and those 1 inch wide by $\frac{3}{4}$ inch thick up to 6 inches wide by 4 inches thick are classified as "flat bars" and "heavy bands." The sizes from 1 to 6 inches wide by $\frac{3}{4}$ to 1 inch thick are standard. A *rod*

is generally understood to be a round bar. *Wire rods* are round bars between 0.2 to 0.3 inch in diameter, and are coiled in bundles. The United States Government limits the term "wire rod" to sizes larger than 0.203 inch in diameter. All smaller sizes are termed "wire." *Hoops* are thin flat sections from ⅜ to 8 inches in width, and from about $\frac{1}{32}$ to $\frac{3}{16}$ inch thick, the thickness generally being measured by standard wire gage measurements. They are coiled in bundles the same as wire rod.

Structural *shapes* — angles, channels, I-beams, T-iron, Z-iron, etc. — derive their commercial names from the shape of their cross-section. *Rails* are subdivided into light and heavy, light rails being those weighing less than 40 pounds per yard. *Plates* and *sheets* are made by passing slabs and sheet bars through plate mills. Plates less than No. 10 U. S. plate gage (0.1406 inch) are generally termed "sheets." The United States Government limits the thickness of sheets to No. 12 U. S. standard gage (0.1094 inch). Ordinarily, sheet mills do not roll stock thinner than No. 30 gage (0.0125 inch). *Skelp plate* is used in the manufacture of tubes and pipes, it being rolled to such, width and thickness as is required for the desired diameter and strength of tubing. The edges are generally sheared for large sizes of pipe. Sheets that are coated with tin are known as "tin plate," those coated with a tin-lead alloy are known as "terneplate," and those uncoated, as "black sheets."

The Rolling Process. — The ingots to be rolled must be at nearly a white heat at the beginning of the rolling process, and the rolling is continued until the heat has been reduced to nearly a red heat. In many plants, the equipment is such that a complete rolling process from the ingot, bloom, or billet to the finished product can be completed in one heat, but, in other cases, the metal bars are cut up into shorter pieces, reheated, and again rolled. The heating of the ingots is done in furnaces, usually heated by gas. In many cases, large ingots are taken directly from the molds into which they have been poured, as soon as the outside has solidified, and are then placed in soaking pits or pit furnaces made of firebrick, in which they are kept until there is a uniform heat in the ingot throughout, so that

they can be properly rolled. The end of the ingot of hot metal is then forced between the rolls and the metal is carried forward by friction. The reduction in thickness that can be made at one passage through the rolls is comparatively small. Grooved rolls, therefore, are so made that a number of passes may be made through each stand with a certain reduction in size, and often some change in form in each pass; but the number of passes that can be made for one heat is limited, when it is necessary to roll out a given section in one heat. The number of passes is also limited by the fact that the length of the central part of the roll into which the grooves are cut should not exceed from $2\frac{1}{2}$ to $3\frac{1}{2}$ times its diameter. As there is always a tendency for round work to be rolled out at the sides with each passage
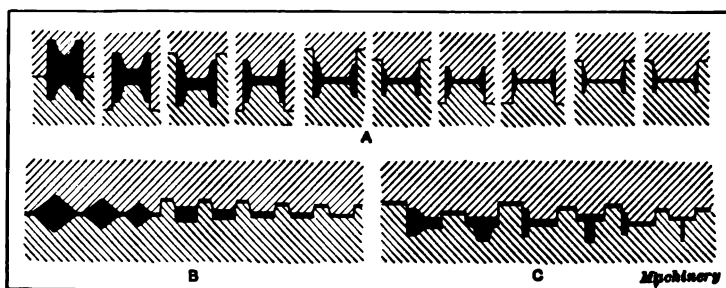
Fig. 2. Successive Passes for Rolling I-beams, Flat Bars, and T-bars

through the rolls, it is turned through an angle of 90 degrees, before it is again passed through the grooves.

The grooves in the rolls used for rolling ingots into rails, structural shapes, and bars are dimensioned with great care in order to obtain the smallest possible number of passes without subjecting the metal to excessive stresses when rolling. There are two classes of grooves, known as "open" and "closed." Open grooves are those that do not intermesh in order to enclose the rolling space, as, for example, the groove shown to the left, at A, in Fig. 2. A roll with closed grooves has a collar that meshes with a corresponding groove in the other roll, in such a way that the shape being rolled is completely enclosed as it passes between the rolls. All the grooves at A, Fig. 2, except the one to the extreme left, are enclosed grooves. The open grooves

are used only for rolling round and square sections, and for the roughing pass for a structural shape; for all other rolling of rectangular bars, rails, and structural material, closed grooves are used. Fig. 2 shows three examples of successive passes in rolling; at *A*, an I-beam; at *B*, a flat bar; and at *C*, a T-bar. In the case of the I-beam, two sets of rolls would be used — one for the five passes shown to the left, and one for the five passes

Fig. 3.   Forty-inch Two-high Blooming Mill

shown to the right.   The first set of rolls is known as the "roughing rolls," and the second, as the "finishing rolls."

Classification of Rolling Mills. — Rolling mills are classified according to their product and the purpose for which they are used. After an ingot has reached the desired temperature in the heating furnace, it passes through the *blooming* or *slab mill*, which is used for reducing ingots to blooms, billets, or slabs. These mills reduce the ingot from a section which may be about

14 inches square to a section about 6 inches square, so that it can be passed into the subsequent forming mills. Blooming mills are usually of the two-high reversing type (see Fig. 3) although the three-high non-reversing type is also employed. The rolls in the two-high mills are from 34 to 48 inches in diameter, and in the three-high mills, from 28 to 42 inches in diameter. The roll-tables of three-high mills, which support the stock as it passes through the rolls, are raised and lowered by a hydraulic arrangement, so that the ingot being rolled is automatically transferred to the level of the rolls that it has to pass through. *Billet mills* are used for reducing blooms to a section of $1\frac{1}{2}$ inch square or larger, so that these billets may be used for rolling bars and rods. Billet mills are generally three-high, with rolls of from 24 to 32 inches in diameter. The billets are cut into certain lengths after having passed through the billet mill, and the sections thus obtained are used for rolling bars and rods. *Sheet-bar mills* are used for rolling slabs and blooms into sheet-bars, which are later used in plate mills for the rolling of plates and sheets. These mills are generally three-high with rolls of from 24 to 32 inches in diameter. In this mill, the slabs are reduced to a section of from 6 to 12 inches wide and not over 2 inches thick. *Beam mills* are used for producing beams and channels 12 inches in size and over. They are generally three-high and have rolls of from 28 to 36 inches in diameter. *Shape mills* are used for rolling smaller beams and channels and other structural shapes. They have rolls of from 20 to 26 inches in diameter. *Rail mills* are generally specially designed. They have rolls of from 26 to 40 inches in diameter. The ends of the rails are trimmed off immediately after rolling with circular saws; as a rule, in rail mills, these saws cut three rails of the required length from one long rolled rail. *Merchant-bar mills* are used for rolling small sizes of bars and rods. The rolls in these mills vary from 16 to 20 inches in diameter, for the larger sizes, down to from 8 to 16 inches in diameter in the smaller sizes. *Plate mills* vary in size from those making armor plate, which have rolls of from 44 to 50 inches in diameter and a body qf from 140 to 180 inches long, to sheet mills with rolls of from 20 to 32 inches

in diameter. In the rolling of flat plates, the horizontal rolls
are adjusted so that the distance between them is reduced after
each passage of the sheet. If a smooth, bright finish is required,
as on some sheet-steel plates, the hot-rolled sheet is pickled to
remove the scale and then rolled cold. Sheets so treated are
known as "cold-rolled" sheets. When large tonnage is desired,
billet, sheet-bar, rod, sheet, and tube mills are made of the
continuous type, which is done by placing a number of two-
high stands directly in front of one another, so that the work
passes through each in turn. The rolls of each stand are driven
at different speeds, the speed increasing as the work increases in
length and approaches completion.

If a mill is provided with both vertical and horizontal rolls,
so that all four sides of a plate may be rolled simultaneously, or
so that structural shapes may be finished completely in that
manner, they are known as *universal* mills.

Wire Rod Rolling. — Bars of small diameter, and particu-
larly those intended for wire drawing, are known as "wire rod"
and are rolled in mills employing a somewhat different principle
from that in regular rolling mills. In the early development of
the iron and steel industry, small two-high, non-reversing mills
with grooved rolls were used, the wire rod being rolled in the
same manner as larger bars. Later, the two-high mills were re-
placed by the three-high type. At the present time, two differ-
ent principles are used for rod rolling mills, known, respectively,
as the "Belgian" or "looping" mill, and the "continuous" type
of mill.

In the *Belgian mill*, which owes its name to the fact that the
practice originated in Belgium, the wire rod is bent as it comes
through the first rolls and at once starts upon its return pass
between the upper rolls in a three-high mill. From the second
pass, the wire rod is bent or looped back again into a third pass,
and so on. As the wire emerges from the final set of grooves, it
is wound on a reel. Mills of this type produce a high grade of
wire rod, but the labor cost is high, and they are, therefore, only
used to a limited extent in the United States, at the present time.
The method can be used after the rods have been reduced to $\frac{1}{4}$

inch in diameter, and the rod may pass through six or seven passes in this way. As the speed of the rolls is the same, the rod, due to the elongation in the rolling process, occupies a larger space on the floor between any two succeeding passes than between the preceding ones. The production can be increased by using a roughing train of rolls detached from the remainder of the mill and driven separately at a lower speed. It is considered a fair production to turn out 25 tons of wire rod of about 0.2 inch in diameter. It is impracticable to roll sections smaller than this, and from this point on, when smaller diameters are required, they are obtained by *wire drawing*.

The Belgian mill has been largely replaced by the *continuous mill*, in which a number of two-high stands are placed one after the other and close together, so that a rod will pass in a straight line through the entire mill without handling. The speed of each set of rolls is so adjusted that the wire is kept taut. Instead of turning the wire at 90 degrees between each passage through the rolls, alternate pairs of rolls are placed in a vertical position, in some continuous mills; but, as this arrangement has the objection of a high maintenance charge, another type of continuous mill was developed in which all the rolls are arranged in a horizontal plane, and the rod turned through an angle of 90 degrees by passing it through guides having spiral grooves on the inside similar to the rifling of a gun barrel. Several grooves may be cut in each guide, so that, as one set of grooves becomes too large through wear, the guides may be shifted to allow the rod to pass through the next set of grooves. As the wire rod emerges from the last stand of rolls, it is wound onto a reel. The sets of rolls are placed close together in order not to expose the hot metal to the air more than is necessary. In the continuous process of wire rod rolling, it is possible for one end of the billet to be in the furnace while part of it passes through the mill and the other end is wound upon a reel. The production has been increased many times as compared with the Belgian mill, 400 tons per day being possible with one continuous mill when a continuous furnace is used. This furnace is automatically charged and discharges the hot billets into the roughing mill

directly in front of the furnace door. A combination of the
looping mill and the continuous mill has also been made. A
continuous roughing mill is used for breaking down a billet to
looping sizes, and then a looping mill is employed for rolling the
wire to the smaller size.

Making Cold-drawn Shafting. — The terms "cold-drawn" and
"cold-rolled" are indiscriminately applied to all grades of shaft-
ing and screw stock with a bright finish; but these two processes
are entirely distinct. Cold-drawn shafting and screw stock are
made by drawing the steel bar through a die, which reduces the
diameter to exactly the required size and imparts a high finish
to the surface of the metal; and cold-rolled shafting is made by
turning the bar to just about the required diameter and then
obtaining the final reduction and finish by passing it through a
machine equipped with burnishing rolls. It will be evident
from this that the rolling process is very different from the
method of treatment to which steel is subjected when it is rolled
hot to reduce the diameter and increase the length of the bar.
Either cold-drawing or cold-rolling imparts a hard surface to
the steel and increases the tensile strength of the bar. In
addition to cold-drawing and cold-rolling, there is a third method
which finds general application in the production of shafting over
three inches in diameter; this consists of simply turning the bar
down to the required diameter, taking particular care to take a
light finishing cut that will leave the surface as smooth and uni-
form as possible. Most shafting and screw stock up to three
inches in diameter is cold-drawn, and shafting above that size
is generally turned.

Steel for Making Cold-drawn Shafting. — Cold-drawn shaft-
ing is made from an open-hearth steel containing about 0.15 per
cent of carbon, which is similar to the grade commonly known
as "machinery" steel. In most plants engaged in the manufac-
ture of cold-drawn shafting, the raw material is purchased from
the steel mill in the form of bars having a diameter from $\frac{1}{32}$ to $\frac{1}{8}$
inch larger than the shafting to be drawn, the amount of excess
metal increasing with the size of the work; but as the produc-
tion of this raw material is an important part of the shafting

industry, a brief description of the method employed will be given.

Molten steel, which has been brought to the required chemical composition by refining in an open-hearth furnace, is poured into ingot molds that produce ingots ranging from 16 to 20 inches square by from 4 to 5 feet in length, weighing approximately from 3200 to 6250 pounds. These are the regular steel works ingots that might ultimately be worked up into a variety of other products in addition to cold-rolled shafting. After being removed from the mold, the ingots are transferred to a blooming mill, in which they are rolled down into billets of from 2 to 5 inches square, according to the size of the shafting to be made.

The next step in the process will depend upon the kind of shafting that is to be produced; but in any case the billets produced in the blooming mill are cut up into pieces of such a length that they can be rolled out into bars of the same length as the shafting to be drawn. In most cases, the length of billet is such that the rolled bars will be from 30 to 40 feet in length, as this is the greatest length that can be handled in an ordinary freight car. The billets are reheated and then rolled down into bars of this length, of a diameter slightly larger than the required size of the shafting.

Pickling Hot-rolled Bars. — The steel bars that the shafting factory purchases from the steel mill have been rolled hot, and as a result they are covered with an oxide scale, which must be removed before the bars can be converted into cold-drawn shafting. The reason for this is that the oxide scale is extremely hard and would rapidly destroy the drawing dies; also, cold-drawn shafting is required to have what is known as a "bright" finish, and this can only be obtained when the metal is free from oxide. Another reason for removing every particle of scale from the bars before they are drawn is that, if it were not removed, small pieces of scale would be driven into the steel by the die pressure and cause flaws that would seriously reduce its strength. The first step in cleaning or "pickling" the metal is to place the bars of steel in wooden troughs containing a 5-per-

cent solution of commercial sulphuric acid, which was a specific
gravity of 66 degrees Baumé at a temperature of 60 degrees F.
The scale is removed by a combined chemical and mechanical
action; the acid reacts with the iron and liberates hydrogen,
which collects under the oxide scale and develops sufficient
pressure to tear away the scale in small plates. As the chemical
action is accelerated by heat, the temperature of the acid bath
is raised to about 180 or 200 degrees F. by means of pipes which
deliver live steam into the trough.

The shafting must be left in the acid bath only long enough
to remove the scale, as otherwise the steel would be eaten away
and the diameter of the bars reduced so that they would be too
small for making shafting of the size for which they are intended.
It is particularly important to regulate the length of time the
steel is left in the acid bath in the case of high-carbon steel, as
experience has shown that the acid tends to decarbonize the steel
at the surface. Low-carbon steel can be left in the bath for from
12 to 15 minutes, and sometimes 20 minutes will not be too long;
but high-carbon steel must not be exposed for more than 4 or 5
minutes. After being removed from the acid bath, the steel
bars are rinsed in troughs containing pure water, after which
they are transferred to troughs containing a solution of lime-
water, which has the property of neutralizing the acid and pre-
venting further action of any slight trace of acid that may still
adhere to the bars. The dipping of the bars in limewater also
has a further valuable purpose; when removed from the bath,
the bars are covered with a solution of limewater, and after the
water has dried off, this solution leaves a deposit of lime which
protects the steel from oxidation by the oxygen in the atmos-
phere. In order to prevent the steel from rusting, it is of the
highest importance that the bars be dried quickly after they are
removed from the limewater bath.

Pointing Bars preparatory to Drawing. — Before the cleaned
steel bars can be subjected to the cold-drawing operation, it is
necessary for them to be pointed at one end so that the point
can be passed through the drawing die and gripped by the tongs
of the draw-bench. The method of pointing varies according to

the size of the bars that have to be drawn, and practice in this connection also varies according to the shop in which the work is done. In general, bars of the larger sizes are pointed in a machine equipped with a cutter-head that actually removes metal from the end of the bar. On smaller sized bars, the pointing is done in a swaging or rolling machine which hammers or rolls down the end of the bar.

Pointing round bars ready for the cold-drawing operation is a simple matter, because the shape of the work offers no particular difficulty; but it is necessary for the shape of the point to be the same as that of the bar which is to be drawn, so that, in the case of square, hexagon, flat, and V-shaped bars, the point must be of the same shape as the finished bar. In order to secure this result special methods must be employed. One of the most satisfactory processes consists of heating the end of the bar and then gripping it on each side of the heated section by clamps on a machine which provides for pulling the bar sufficiently to "neck in" the heated section and point it. Those who have conducted tests on a testing machine will recall that, in stretching hexagon and other shaped sections, the neck produced holds the shape of the original bar. Where this method is employed for pointing bars ready for drawing, it is important not to exceed the elastic limit of the material, as such a condition would result in a rapid reduction of diameter. To overcome this condition, the operator of the machine has a sponge soaked in water, and as soon as he notices any tendency for the diameter of the bar to reduce rapidly at some point, he drops a little water on the metal so that the temperature is lowered and the metal hardens sufficiently to prevent further reduction in diameter at the point where the elastic limit has been exceeded.

Starting the Bar through the Die. — The carriage on a draw-bench is furnished with two serrated jaws that grip the work. These jaws are tapered on the outside and fit into a tapered holder on the carriage; the result is that, when the jaws are pressed against the work and the carriage starts forward, they are drawn back in their tapered holder, which forces them to secure a firm grip on the work. For drawing stock over one inch

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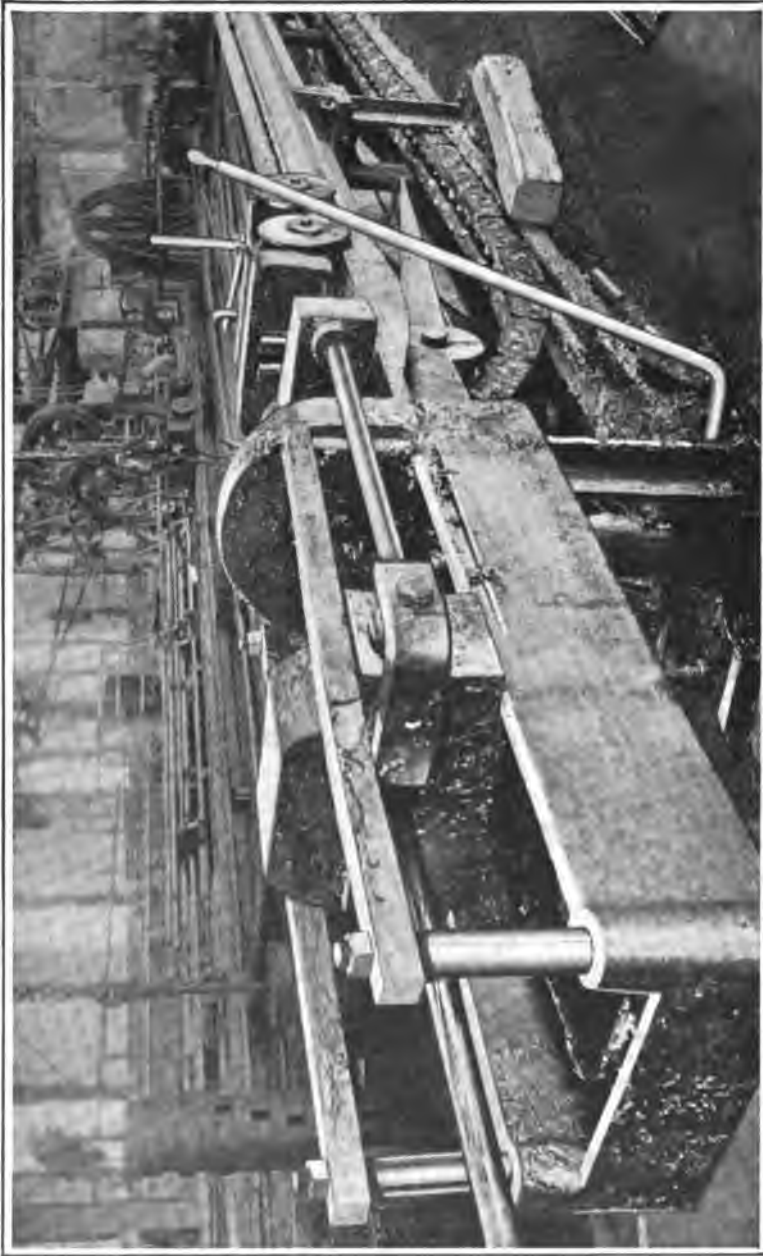
Fig. 4. Draw-bench equipped with Device for Gripping Bar behind Die; Extension on Gripper is caught by Draw-bench so that the End of the Bar is pushed through the Die Ready to be drawn

in diameter, some manufacturers have their draw-benches equipped with an auxiliary carriage located behind the die-holder (see Fig. 4), which is fitted with a pair of tapered serrated jaws that can grip the work.   Attached to this carriage is a yoke that drops over the die-holder so that a bar at the front end of the yoke may be gripped by the jaws of the regular draw-bench carriage.   When the main carriage is started, this yoke draws the auxiliary carriage forward, which results in pushing the front end of the bar of steel through the die.   Fig. 5
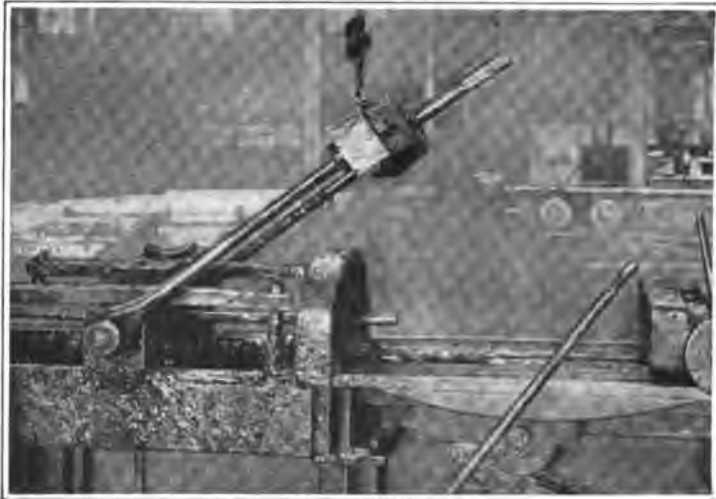
Fig. 5.   View of Die from Front after End of Bar has been pushed

shows the apparatus on another draw-bench after the bar has been pushed through the die and the yoke released from the jaws of the main carriage and raised by means of the cable and counterweight furnished for that purpose.   The operator will now draw the main carriage back and grip the projecting end of the bar between its jaws; he will then release the jaws of the auxiliary carriage from the work and start the draw-bench, to pull the bar through the die.   This is the means of saving the crop end of steel, which results through the customary practice of pointing the end of the bar so that it may be threaded through the die.   On bars less than one inch in diameter, this method

cannot be used, because the bar buckles instead of being pushed through the die.

Types of Draw-benches Used. — Two types of machines are generally used for drawing shafting and screw stock. The first of these is known as the "straight draw-bench" (see Fig. 6), on which a straight rod (and sometimes more than one rod) is drawn through the die by means of tongs on a head which travels along a straight line on the draw-bench, power being furnished by an endless sprocket chain or by hydraulic pres-
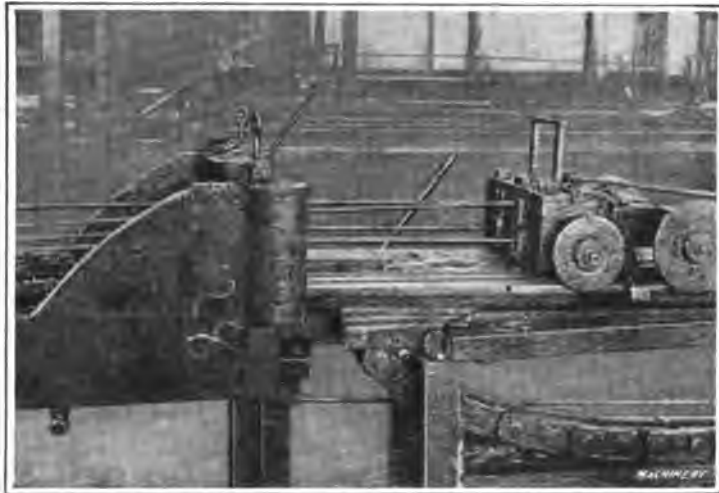
Fig. 6.   Straight Draw-bench pulling Four Rods Simultaneously

sure.   The second type is the bull-block or rotary machine (see Fig. 7) on which the rod is in the form of a coil that is carried on a reel at one end of the machine; the end of this rod is pointed and threaded through the drawing die and gripped by tongs carried on a second reel, which rotates in such a way that the rod is drawn through the die and wound up on the second reel.   Both types of machines have points in their favor.

The straight draw-bench is generally used for shaftings and rods from ⅛ inch in diameter and up; the most obvious advantage claimed for it is that the material is always straight, and consequently requires little treatment after the drawing opera-

tion has been completed. The bull-block machine winds up the cold-drawn steel in a coil, which must be carefully straightened to prepare it for use. This takes time and involves an additional item of expense in the process of manufacture; but there are a number of factors in the bull-block machine that offset this expense, if they do not actually introduce a material factor of saving. In the first place, the material in coils is much more convenient to transport through the plant, as the stock can be carried on trucks and the plant does not have to be laid out in such a way that long bars can be handled conveniently. In the second place, it is possible to draw coils of steel weighing from 300 to 400 pounds and containing anywhere from 300 to 600 feet of rod, according to the diameter; consequently the cost of production is much less because the number of crop ends and the amount of scrap metal are greatly reduced. In fact, this is the most important claim made for the bull-block machine. The rate of production is also higher, because the time spent in setting up the machine is less where these long coils can be drawn at one continuous operation. Practice varies in different plants, but as a general rule straight draw-benches are used for handling stock from $\frac{1}{2}$ inch in diameter and up, while bull-block machines are used for stock up to $\frac{1}{2}$ inch. However, there are a number of cases in which bull-block machines have been successfully employed for drawing bars up to $\frac{3}{4}$ inch in diameter. Squares, rectangles, hexagons, octagons, and other irregular shapes are being drawn on bull-blocks in addition to round stock.

Where the attempt is made to draw stock larger than $\frac{3}{4}$ inch in diameter, trouble has sometimes been experienced through the tendency for the cross-section to be slightly distorted. For instance, in round stock the tendency is for the cross-section to become slightly elliptical. This is due to the fact that the material is being coiled on a comparatively small drum, and trouble of this kind is especially likely to happen when low-carbon steel is being drawn. Sometimes it has been found possible to compensate for this in the shape of the die or by employing special methods of straightening the stock. There is a wide difference of opinion, however, as regards the maximum

IRON AND STEEL

Fig. 7. Rotary Draw-bench built by Humphrey & Sons and installed at Youngstown Sheet & Tube Co.'s Plant

diameter of stock that can be safely handled on rotary drawing machines. As previously stated, some manufacturers will not attempt to draw work over ½ inch in diameter, while others are successfully using machines of the rotary type for drawing work up to round bars ⅞ inch in diameter.

Rotary Type of Draw-bench. — The rotary type of draw-bench or bull-block shown in Fig. 7 was built by Humphrey & Sons, Joliet, Ill., and is installed in the plant of the Youngstown Sheet & Tube Co., Youngstown, Ohio. The capacity is for drawing steel up to ½ inch in diameter. The first block A at

the right-hand end of the bench is not in operation, although it is in position to be threaded up ready to start work. Just at the right of this block and projecting up through the bench there is a lever B which is so arranged that if a man is caught by the wire between the die and the block, while feeling the wire to see if the die is working properly, his body is drawn up on the bench and strikes this lever, which automatically stops the block rotating and prevents a serious accident. Accidents of this kind are by no means uncommon among wire mill operators, and unless means are provided for stopping the machines the accident is likely to be a severe one. At the front of the die-stand or die-holder there will be seen a guard ring C, which is a further device to provide for the operator's safety. In case he is caught by the wire between the reel-stand which holds the coil of steel and the die, his body is drawn up against this guard ring, which automatically operates an air valve that stops the bull-block from rotating.

On top of block A at the right-hand side there will be seen what are known as "pullers" D hanging down at the side of the block. These are drawn forward with the right hand and attached to the point of the steel that projects through the die, after which the block is ready to be started rotating to draw the steel through the die and wind it up on block A. Between blocks A and E is a pointing machine F, which is used for pointing the end of a coil of steel so that it may be threaded through the die to be gripped by the pullers. This pointing machine is driven by a chain drive from the lineshaft and is of the continuous type, i.e., the pointing rollers always run in the same direction instead of oscillating as they do in another type of machine for pointing stock. In the rollers there are cut grooves, the cross-section of which is gradually reduced so that, as the wire is drawn through, its diameter is reduced sufficiently so that the point may be threaded through the die in the manner described.

Bull-block E is shown after the wire has been finally drawn through the die and the bundle has been partially stripped off the block. Block G has a wire threaded up through the die and the block is ready to start making the draft. Block H is shown

engaged in the operation of drawing wire, and is partially covered with drawn wire. Blocks *I* and *J* are not shown in any special positions.

After the drawing operation has been started, the wire is gaged to see that it is true to size; and when the operator of the draw-bench is satisfied that this is the case, he starts the bull-block again and draws all the wire through the die. After the steel has been drawn through the die, it is ready for the market as soon as the pointed end has been cropped off and the bundle of wire has been gaged at both ends to see that the variation in size between the two ends is within the required limit of accuracy. In both cold-drawn shafting and cold-drawn wire, this limit will not exceed 0.0005 inch if the work is properly done. Some variation is bound to exist due to wear of the die, and the amount of error will usually depend upon the quality of the die and the care with which the steel and die are lubricated during the drawing operation. Other factors that affect the degree of accuracy obtained are the amount of reduction required from the rod to the finished steel, quality of the steel, care taken in the pickling operation, and care taken in drying the stock after it has been immersed in the lime bath.

Speeds at which Cold-drawing is done. — The speed at which cold-drawn steel stock or shafting is pulled through the die varies considerably with the size of the stock being drawn. The larger the diameter, the lower must be the rate at which it is drawn through the die. Bull-blocks or draw-benches are not arranged to give a variable speed, but the gearing and diameter of the blocks on a bench may be varied, thereby accomplishing the same results. Most steel mills drive their blocks with electric motors, a motor driving from one or two blocks up to any number within the range of its capacity. The actual drawing speed varies from 250 to 375 feet per minute, according to the diameter of the wire and the character of the steel being drawn. The following represents the practice of the Pennsylvania Shafting Co., Spring City, Pa., in drawing steel shafting on straight draw-benches. On a bench handling four bars at once (see Fig. 6), ranging from $\frac{7}{8}$ to 1 inch in diameter, the speed at which the

steel is drawn through the dies is 16 feet per minute. For stock from $1\frac{1}{16}$ to 2 inches in diameter, drawing one bar at a time, the speed is 16 feet per minute. When drawing steel from 2 inches in diameter to $3\frac{1}{4}$ inches, with one bar drawn at a time, the speed is 8 feet per minute. In the case of flat bars ranging in size from $\frac{1}{4}$ by 5 to 1 by 5 inches, and hexagons of about the same cross-sectional area, the speed of drawing is 11 feet per minute. In drawing bars from $\frac{1}{4}$ to $1\frac{1}{8}$ inch square or $\frac{1}{2}$ by $1\frac{3}{4}$ inch flat, a drawing speed of 16 feet per minute will give satisfactory results.

Reduction of Stock by Cold-drawing. — In conducting the cold-drawing operation, the entire reduction is obtained by one passage of the steel through the drawing die. The amount of reduction obtained varies according to the diameter of the shafting which is being drawn, but for sizes $\frac{1}{2}$ inch in diameter and over, a reduction of $\frac{1}{16}$ inch may be obtained; and for smaller sizes of shafting, the reduction is about $\frac{1}{32}$ inch. In drawing some large sizes of shafting, a reduction as high as $\frac{1}{8}$ inch is obtained. The bars of steel ordered from the rolling mill are specified to have a diameter which exceeds that of the shafting to be produced by the amount of reduction which may be obtained by one passage through the drawing die. The reductions referred to are for steel containing 0.15 per cent of carbon; for high-carbon steel used in the manufacture of drill rod and certain other products, the amount of reduction possible by one passage through the dies is much less, as it is found that where the reduction is too great there is a tendency for the fibers of the metal to break and thus cause a serious reduction in the strength of the bars; consequently, the drawing of drill rod is conducted in such a way that a number of reductions are obtained by successive passages of the steel through the drawing dies until the diameter of the bar has been reduced to exactly the required size. For bars up to $\frac{1}{2}$ inch in diameter, the amount of reduction at one draft is $\frac{1}{32}$ inch; for bars from $\frac{9}{16}$ to 3 inches in diameter, the amount of reduction per draft is $\frac{1}{16}$ inch; and for bars from $3\frac{1}{16}$ up to 6 inches in diameter, the amount of reduction per draft is $\frac{1}{8}$ inch. Bars over 3 inches in diameter can be most profitably finished by turning. The heavier the draft the smoother and

cleaner the surface of the cold-drawn steel; but extremely heavy drafts require more power, and in the case of alloy steels or steels containing a high percentage of carbon, such heavy drafts may disturb the structure of the steel and make it unsuitable for the desired use, although a superior finish is obtained.

Advantages of Cold-drawing Process. — Two important advantages are secured from the process of cold-drawing: First, the metal does not oxidize, because the work is done cold, and as a result the steel retains a so-called "bright" finish. Second, it is possible to hold the material within very close limits, the diameter of good cold-rolled shafting or screw stock being within 0.0005 inch of the specified diameter. The clean and extremely smooth finish produced in this way enables a high transmission efficiency to be obtained with cold-drawn shafting, as friction losses in bearings are reduced to a minimum. Advantage is taken of this method in producing material used for various other purposes, such as the manufacture of parts in automatic screw machines, etc., as it is found that the smooth finish and uniform diameter of cold-rolled drawn bars enable them to be handled by automatic machinery with much better results; and advantages may also be taken of the high finish of the bar to avoid the necessity of further machining of surfaces where the original diameter of the bar meets all requirements. In this way a considerable saving is made in both material and production time.

Dies Used for Drawing Small Stock. — There are two general classes of dies used for drawing screw stock. These are, first, the chilled cast-iron die, and, second, the so-called "steel die-plate." Cast-iron dies are made with one opening for drawing a specified size of steel, while in the die-plates there are a number of openings, which are used in succession until all have been worn over size. Although the method of drawing steel through these types of dies is the same, the practice in maintaining the dies in proper condition for use is quite different. In drawing steel through either type of die, it will be obvious that friction gradually wears the die over size, and when the limit of over size for drawing a given diameter of steel has been reached, the methods of putting the two types of dies into condition for further use are

quite different. In the case of a cast-iron die that has reached the limit of over size allowable, the method of procedure is to remove the die from the draw-bench and ream out the hole to the minimum diameter allowable for drawing the next larger size of steel made in the mill where this die is used.

With steel die-plates an entirely different procedure is followed. The die-plate is heated and hammered on the "leaving" or back side of the die, so that the steel is forced inward around the hole, reducing its diameter slightly more than the required amount. It then goes to a man known as a "plate setter" who uses a tapered punch which he hammers into the hole in the die while the metal is cold, thus compressing the steel around the hole and at the same time enlarging the hole to the minimum diameter which is allowed for drawing a given size of steel. Steel die-plates were once used almost exclusively in the United States for drawing steel wire and small sizes of screw stock, but at the present time cast-iron dies are more extensively employed for drawing round wire. For shapes other than rounds, i.e., ovals, half rounds, squares, hexagons, etc., it is probable that steel die-plates will continue to be used because of the difficulty that would be experienced in maintaining cast-iron dies in suitable condition for operation. This is, of course, due to the fact that irregular-shaped die openings cannot be reamed. In Europe and especially in English wire mills, steel die-plates are still generally used.

Although steel plates can be used repeatedly for drawing wire of the same sized hole, while cast-iron plates have to be reamed out for a new size of wire each time they are used, the original cost of the steel plates and the labor expense involved in setting them back for drawing the same size wire are greatly in excess of the cost of the cast-iron die and the labor charge involved in reaming it out to permit a larger size wire to be drawn. Chilled cast-iron dies and steel die-plates are usually made for drawing stock up to $\frac{1}{2}$ inch in diameter; in some cases, larger stock is drawn in these dies.

Dies for Drawing Shafting and Larger Sizes of Screw Stock. — For drawing the larger sizes of screw stock and all sizes of

shafting, there are several types of dies that are commonly employed. For drawing round stock, the most commonly used die consists of a disk of high-speed steel with a round opening which is bell-mouthed, tapering gradually down to a straight throat of the same diameter as that of the steel which it is desired to draw.

There are two types of drawing dies in general use which are known as the "hard" die and the "soft" die. As their names imply, the steel in these two types is hardened or left soft as the
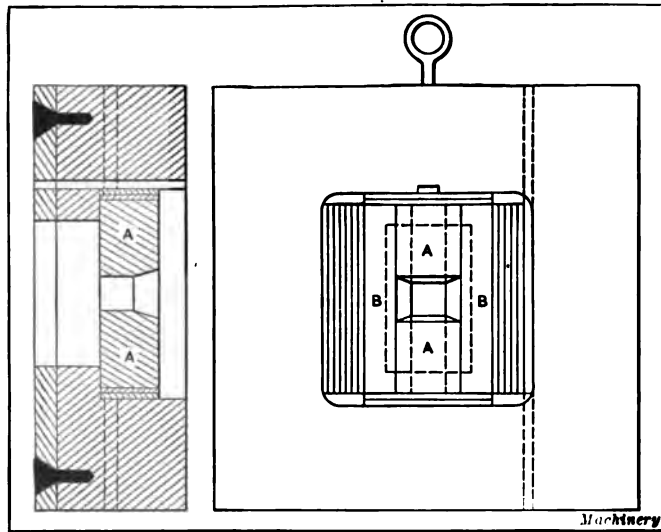
Fig. 8. Front and Cross-sectional Views of So-called "Turk's Head" or Combination Die

case may be, and each form has certain points in its favor. The hard die is made to exactly the required form and size, after which it is heated and quenched by passing a stream of cold water through the opening. This results in hardening the metal so that the die is able to draw from 500 to 1500 40-foot bars according to the nature of the steel in the bars and in the dies through which they are drawn. Soft dies have a capacity for drawing only from 12 to 15 40-foot bars, but they are easily put back into condition for further service. This is done by hammering the dies at the "leaving" side, which results in

causing the metal to flow in and reduce the diameter of the opening, after which the hole is reamed out to exactly the required size. This work can be done rapidly.

In the case of the hard die, it is necessary to heat it above the critical temperature and then pass a stream of cold water through the opening, which causes the inner part to shrink sufficiently to draw in the hot outer section, thus reducing the diameter of the hole beyond the required size, after which the die is lapped out to secure the correct diameter. This is necessarily a slow and costly operation, so that, although the hard die has a far greater capacity as regards its productive life, the cost of putting it back into condition after it is worn out is much greater than in the case of the soft die.

Dies used for Drawing Squares, Rectangles, and Irregular Shapes. — Different methods must be followed in designing
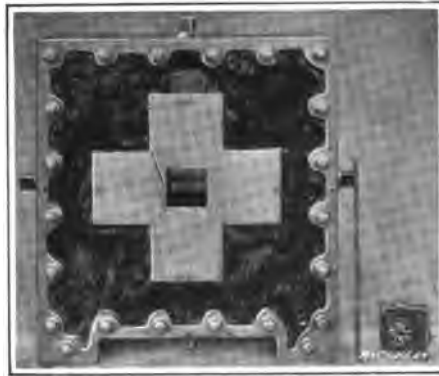
Fig. 9. Roller Die built by Standard Machinery Co. for Drawing Square Bars

dies for drawing square and irregular-shaped bars from those used in making dies for round stock, because trouble would be experienced in maintaining solid dies of these shapes in the required condition. Some dies for drawing squares, hexagons, and octagons are made from solid blocks, but it is probably better practice to use either a die of the type known as a "Turk's head" or one of the special dies constructed with rollers that engage the stock to be drawn. Fig. 8 shows the Turk's head type of die, and Figs. 9 and 10 show front and rear views of one of the rolling type of dies.

The Turk's head die has a steel frame in which are supported two pieces *A*, known as "distance pieces," and two side pieces *B*. These four parts are securely wedged in place in the frame, so that the die opening is kept the desired size. Compensation for wear of the die is made by adjusting the position of the side

pieces and distance pieces with wedges in the die frame. The distance pieces and side pieces are fitted together in such a way that the pressure applied in drawing the steel through the die cannot result in pulling either of the die members out of place. The die opening is arranged with a bell-mouth tapered from 5 to 7½ degrees according to the hardness of the stock to be drawn. In addition to making dies of this type for drawing squares and rectangles, the same type of die may be employed for drawing bars with straight sides and semi-circular sections at the top and bottom. For drawing hexagons and octagons, sectional dies of this type are made with the sections adjusted radially by means of screws.

The particular rolling mill die shown in Figs. 9 and 10 is for drawing square-shaped stock, and it will be apparent that four hardened steel rollers are arranged to bear against the four sides of the stock and reduce it to the required diameter. Obviously the form of the rollers provides a die opening corresponding to the bell-mouth of either a solid or a "Turk's" head die. The opening in the die can be adjusted to any size within its limits without changing the rolls, by simply turning the square-headed screws provided for that purpose. These screws are furnished with graduated dials to facilitate setting.

Lubricants Used on Drawing Dies. — Lubrication of the steel and cold-drawing dies is very important. If even a small area of steel is drawn into the die without being properly coated with lubricant, it will "seize" and do much damage through scoring the surface of the die opening. A variety of different lubricants are used on drawing dies, and each manufacturer of cold-drawn screw stock and shafting has certain lubricants of which he speaks

Fig. 10. Opposite Side of Roller Die shown in Fig. 9

in high terms. At the plant of the Pennsylvania Shafting Co., two different mixtures are used for lubricating the dies. One of these is compounded from tallow, heavy machine oil and soap powder. These constituents are mixed in such proportions that, when heated and thoroughly stirred together, the resulting lubricant will be of such consistency that it can be easily rubbed onto the bars by hand as they are being drawn through the die. The other standard lubricant used by this firm is made of a mixture of cup grease, heavy machine oil, and soap powder. As in the preceding case this mixture is heated and thoroughly stirred, and should be of suitable consistency to be easily rubbed onto the work.

Liquid lubricants are also used in some mills. An advantage resulting from their use is that means are devised for applying the lubricant to the steel bars and dies through which they are being drawn without requiring the workmen to apply grease by hand. One way is to take a large bundle of waste and soak it thoroughly in oil, after which the waste is wrapped around the steel bar and allowed to be drawn up against the die. In this way the waste is held in place against the "entering" side of the die and keeps the bar thoroughly lubricated as it is being drawn through. Care in the application of a lubricant will probably have a greater effect upon the cost of the lubricant used and the efficiency with which it operates than the selection of any particular type of oil or grease.

Straightening and Cutting Cold-drawn Bars. — The practice followed in straightening cold-drawn bars naturally differs according to the diameter of the bar and whether it was drawn in a straight draw-bench or a bull-block machine. In the case of shafting and bars drawn on the straight bench, the bars are passed through a straightening machine, which consists of a rotary cradle that supports staggered rolls. (See Fig. 11.) While the shafting is being drawn through the cradle, the latter rotates around the bar or shaft being straightened. The rollers impart a fairly high polish to the steel drawn through them. In the case of long coils of metal that have been drawn on a bull-block, a similar form of straightening machine is used, but, in addition,

provision is made for cutting the work into pieces of standard length. For this purpose, the bar is drawn through the rolls carried in the rotary cradle, and when the end has been drawn through the required distance it comes into contact with the trip or trigger on the machine, which results in actuating a shear blade that cuts off a piece of standard length. The position of this trigger may be adjusted to provide for cutting off bars of any required length, which may be as short as two or three inches or up to practically any desired length.
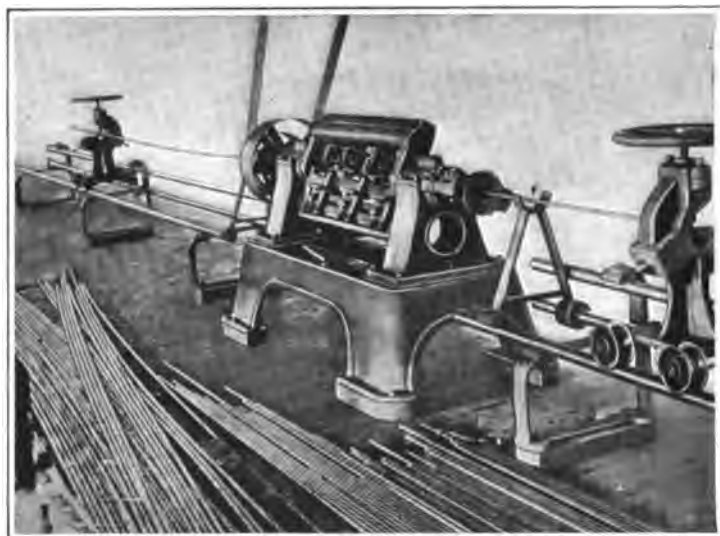
Fig. 11. Rotary Type of Shaft-straightening Machine built by Bright-man Mfg. Co.

Another type of machine for straightening round bars, which has been found to give very satisfactory results, is the Medart straightener built by the Medart Patent Pulley Co., St. Louis, Mo., shown in Fig. 12. This machine has only two rollers, one of which is a straight cylinder and the other slightly concave. These rollers are set with their axes at a slight angle to each other and the rollers are driven in opposite directions by means of universal joints and shafts. One end of the bar to be straightened is inserted between the rollers, and the angular position of the rollers, combined with the fact that they rotate in op-

posite directions, results in drawing the bar through the machine at a rate of from 20 to 30 feet per minute. The effect of rolling a bar between the straight and concave rollers is practically the same as drawing the bar through a set of staggered rollers on the type of straightening machine to which reference has just been made. The Medart straightener is adapted for handling bars up to three inches in diameter, and one feature claimed for it is that a particularly high polish is produced.

For straightening square, rectangular, hexagonal, and octagonal bars, a different type of straightening machine must be em-
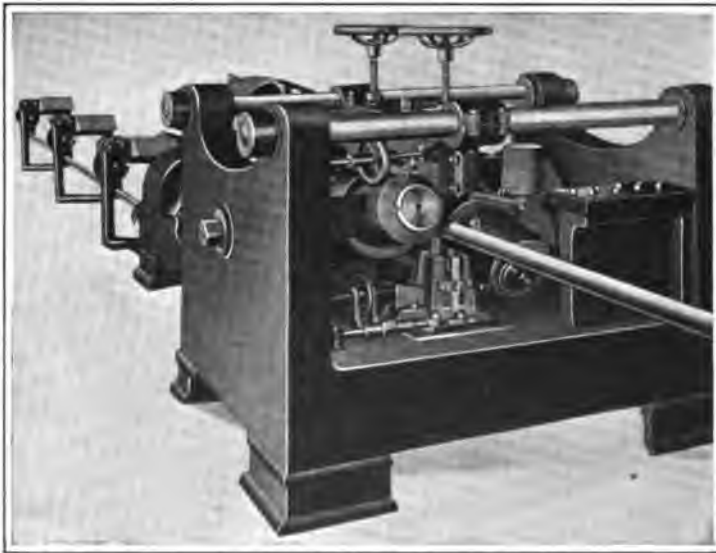
Fig. 12. Medart Straightening Machine

ployed from those that have been described. The type of machine used for this purpose is shown in Fig. 13. It consists of two sets of five pairs of staggered rollers, those for straightening the bars sidewise being located between the housings of the machine, while the rollers for straightening the bars edgewise are located outside the right-hand housing, as shown in the illustration. Work is passed through the machine at a rate of about 25 feet per minute. The bars are given two passes through these rollers for each pair of opposite sides of the bar, i.e., a

square bar receives a total of four passes, while an octagon-shaped bar requires eight passes to completely straighten it.

After being straightened and polished, the steel is usually wrapped in wax paper and then in burlap, so that adequate protection is provided against rusting in transit. As one of the important advantages obtained by the cold-drawing process is that the steel is given a bright finish, it is essential to protect it

Fig. 13.   Machine for Straightening Square, Hexagonal,
Octagonal, and Flat Bars

against oxidation. In some cases the burlap bundles of steel are packed in wooden boxes so that they are held straight, thus assuring delivery to the purchaser in the best possible condition.

Cold-rolling Strip Steel. — Cold-rolled steel possesses several advantages which cannot be secured with metal that is rolled hot. Most noteworthy of these is the fact that rolling the metal cold enables it to be given a so-called "bright" finish; that is, there is no oxide or stains on its surface. Where the

steel is rolled hot, this advantage cannot be obtained, because hot metal is easily attacked by oxygen of the air that results in forming the well-known scale with which heated metal is covered. Those who have had experience in the working of sheet steel know that this oxide scale is exceedingly hard, and that it exerts a very harmful effect on the dies. For this reason, cold-rolled steel is in demand for use in the manufacture of various pressed steel products. In addition to the advantage secured through the absence of scale in working cold-rolled steel under the punch press, the possibility of rolling steel without forming any scale has another important advantage. Sheet metal produced in this way can be rolled very thin — the limit being about 0.003 inch — and the thickness can be held within close limits. It will be evident that this would be utterly impossible if the metal were at a red heat, because the production of scale would not only cause considerable variation in the gage of the metal, but with extremely thin sheets it would actually result in its complete destruction.

Mills engaged in the manufacture of cold-rolled steel secure their raw material in the form of hot-rolled ribbon stock of a thickness somewhat greater than that of the cold-rolled steel which is to be produced. The treatment of this material in early stages of the process will differ according to its carbon content. With steel which does not contain over 0.30 per cent of carbon, it is unnecessary to conduct a preliminary annealing process; but steel with more than 0.30 per cent of carbon must be annealed before the rolling can be started. In describing the method of manufacturing cold-rolled steel, assume that the mill is working on high-carbon steel which requires a preliminary annealing in order to make it soft enough to be rolled advantageously. Three forms of annealing furnaces are employed for this purpose, and the selection of the particular form of furnace to use will depend upon the analysis of the metal. These furnaces are known as the "gas medium" annealing furnace, the "pot" annealing furnace, and the "muffle" annealing furnace. In the muffle furnace, the metal is heated in contact with the air, so that an oxide scale is formed over it, while in the pot

furnace and the gas medium furnace, the metal is protected from the air, so that all tendency to oxidize is avoided. One of the latter types of furnaces is generally used, but the muffle or "scale" annealing furnace is employed where the stock which is to be converted into cold-rolled steel has been treated in such a way that its surface has become decarbonized. With such material, the production of a scale on the surface of the steel is an advantage, because it removes that part of the metal from which the carbon has been withdrawn. This will be referred to in more detail in connection with the description of the pickling process. In all types of furnaces, the temperature employed varies from 1150 to 1300 degrees F., according to the carbon content of the steel. The methods to be described are employed in the production of cold-rolled strip steel at the plant of the Schwartz-Herrmann Steel Co., Floral Park, Somerville, N. J.

Annealing in a Gas Medium Furnace. — The process of annealing steel in the gas medium furnace consists primarily of raising its temperature to the required degree and then allowing the metal to cool slowly. This result is accomplished by placing the coils of ribbon stock on a chain conveyor which carries them through the furnace. The conveyor is driven by an electric motor which transmits power through a train of high reduction gearing, so that it takes about six hours for the steel to pass through the furnace. The conveyor carries the steel through a steel tube surrounded with firebrick in the heating furnace, which is built around the portion of this tube in which the heating of the steel is conducted. The furnace is of simple construction, consisting of a checkerwork of firebrick which is kept at a red heat by the combustion of producer gas; and in order that the furnace may operate at the maximum economy, the draft in this furnace is arranged in such a way that the gas and hot products of combustion pass through the furnace in a winding course which has somewhat the form of the letter S. In this way, the gases leave the furnace at a relatively low temperature, having given up most of their heat to the brick checkerwork.

As the essential difference between hot-rolled and cold-rolled steel is that the latter is entirely free from oxide scale — and as

the method of manufacture is carried on with the view of elimi-
nating scale — it will be evident that in the preliminary treatment
of the metal it is desirable to avoid scaling as far as possible.

Such being the case, the annealing must be conducted in an
atmosphere which is free of oxygen, and this result is obtained
by having the tube in the annealing furnace filled with producer
gas. This gas enters the tube at one end and passes through
to the opposite end, where there is a burner that provides for
consuming the gas as it leaves the tube. It will be seen from
Fig. 14 that the conveyor tube rises at a gradual angle until it

Fig. 14. Entering End of Gas Medium Furnace for
Annealing Steel

has passed through the furnace, after which it drops to the floor
level, where the end of the tube dips into a water seal shown in
Fig. 15. In passing through the portion of the tube contained
in the furnace, the temperature of the steel is raised to the degree
required by the composition of the steel, after which it is carried
along by the slowly moving conveyor, so that its temperature is
allowed to drop very gradually, and this results in annealing the
steel so that it is soft enough to be worked under the rolls. The
steel is quite cold at the time it reaches the water seal at the far
end of the tube, and although it is immersed in the water before
leaving the conveyor, this does not result in the production of
any serious amount of scale or rust. It takes about six hours

for a coil of steel to pass through the furnace, and the rate of production is from 15,000 to 20,000 pounds in 24 hours. The furnace is in operation continuously.

Pot Annealing Furnace. — In the pot annealing furnace, as in the type of furnace which has just been described, the object is to conduct the annealing operation in such a way that there will not be any tendency to form scale on the metal. In pot furnaces, the coils of metal are placed in steel pots and packed with fine iron borings, after which the cover is put on the pot and the joint sealed with fireclay. The iron borings serve to exclude

Fig. 15.   Delivery End of Gas Medium Furnace—Note Arrangement of Water Seal

air from the pot and also to assist in taking up oxygen from the small amount of air which is left; in addition, they have been found to possess the power of absorbing foreign matter from the surface of the steel which would otherwise result in the production of stains on the bright surface of the cold-rolled metal. Each of the pots in which the steel is annealed has a capacity of 1000 pounds of steel coils, and they are of the form shown in Fig. 16. There is a draft up through the center of the pot and lid, to allow the heat to reach the metal from all sides. Eight pots can be held in each furnace at a time. It takes about 12 hours to anneal the steel in this furnace.

The furnaces in which the pot annealing operation is conducted (see Fig. 16) are similar in form to muffle furnaces except that they are provided with doors at the front and back. Gas and air enter the furnace through ports arranged alternately all the way down one side. The flame rises to the arch from which it is deflected to the opposite side of the furnace and escapes through a similar series of ports to those through which the air and gas are admitted. When one pot has been in the furnace for the required length of time, the back door is opened and this pot is withdrawn and allowed to stand for about 18 hours in order to allow the steel to become quite cool before the cover is

Fig. 16.   Pot Annealing Furnace, showing Pot just drawn out

taken off. After withdrawing this pot, the back door is closed and the front door of the furnace is then opened and a truck carrying a pot of unannealed steel coils is pushed in, with the result that all the pots in the furnace are moved toward the back. It will be evident from this that the operation is continuous. Small "peep holes" in the furnace doors provide means of viewing the interior of the furnace without opening the large door.

Muffle Annealing Furnace. — The muffle furnace, in which the steel is given what the cold-rolled steel-maker designates a "scale anneal," is of exactly the same form as the furnace in

which the pot annealing operation is conducted; but in operating this furnace the coils of steel are placed on trucks where they are exposed to the action of an oxidizing atmosphere. These trucks are passed through the furnace in the same way that trucks carrying the annealing pots are handled, and the steel comes out coated with an oxide scale which results in removing a certain amount of metal from the surface of the stock during the subsequent process of pickling. As previously mentioned, this method of annealing is only employed in the case of steel which has become decarbonized at the surface, the scale anneal serving to remove the decarbonized metal. It requires about 2½ hours to perform the annealing process in this type of furnace; and after being removed, three hours are required for the steel to cool sufficiently to be sent to the pickling department. The rate of production is about the same as that of the pot annealing furnace.

Pickling Stock before Cold Rolling. — The preceding description of the preliminary annealing process to which the steel is subjected refers to metal containing not less than 0.30 per cent of carbon, and after such steel has been annealed, it goes to the pickling department, where it is subjected to a treatment which removes all the oxide scale that was produced on the metal during the hot-rolling operations by which it was drawn out from the ingot into the form of ribbon stock. Steel with less than 0.30 per cent of carbon does not need a preliminary annealing, but goes direct to the pickling department. From this it will be evident that, after annealing, high-carbon steel is treated in the same way as steel with a low-carbon content, so that the following description applies to both classes of material.

The pickling process consists of immersing the rolls of steel in vats of sulphuric acid which acts upon the metal and causes the scale to be removed. This acid is contained in wooden vats which are furnished with steam pipes for heating the acid so that it will act more rapidly. The acid consists of a 5-per-cent solution of sulphuric acid which has a density of 66 degrees Baumé at a temperature of 60 degrees F. In pickling, the coils of steel must be loosened sufficiently so that the acid can easily

find its way between the surfaces of the metal. The coils are supported on wooden frames which are lifted by an electric hoist that runs on a track passing over the vats. These frames are dropped so that their ends are supported by the sides of the vat while the metal is immersed. In the case of low-carbon steel, the time that the metal is left in the vat is not important, as it may be immersed for as long as 15 minutes without being damaged. With high-carbon steel, however, great care must be taken, as it requires about three or four minutes to remove the scale, while leaving the steel in the acid for a greater length of time will result in withdrawing carbon from the metal. The removal of the scale from the steel is the result of a combined chemical and mechanical action. The sulphuric acid reacts with the iron to liberate hydrogen gas which sets up a pressure between the steel and the scale and results in stripping off the scale. It is important for the stock to be uniformly covered with scale before pickling; otherwise, the pickled stock will have a "pitted" surface and, therefore, cannot be converted into good cold-rolled steel.

After the pickling operation has been completed, the steel must be washed immediately in order to remove the acid. This is done by lifting out the wooden frames from the acid vats and running them along on the hoist so that they may be dropped into similar vats filled with pure water which washes away the acid so that further action upon the steel is prevented. The removal of the acid would probably be effectually done by washing in water, but, to make sure, the steel is removed from the water and plunged into a vat containing a dilute solution of limewater. The lime has the power to neutralize acid, but in the case of preparing steel for cold rolling, the use of limewater has a further advantage. This is due to the fact that, when the steel is removed from the vats and given time to dry, it is coated with a film of lime which keeps both air and moisture from coming into contact with the metal, and thus prevents it from rusting.

Cold-rolling Operation. — The cold rolling is done in mills of the type shown in Figs. 17 and 18. Two sizes of mills are used which have rolls six and eight inches in diameter; and although

both mills can be used for many sizes of stock, it is found eco-
nomical to distribute the work among the mills according to its
size. In cold rolling it is highly important to avoid chatter and
vibration, as such a condition would be shown by irregularities
in the surface of the product. This provision is well taken care
of by having the power transmitted to the rolls through herring-
bone gears and shackle bars which serve as a double precaution
against vibration and result in a very uniform transmission.
The rolls are made of hardened chrome-vanadium steel contain-
ing a small percentage of tungsten, and are carefully ground to
give them a very smooth finish. While in operation, the rolls

Fig. 17.   Cold-rolling Strip Stock

are water cooled by a continuous stream of water that flows
through a pocket in the center of each roll. The position of the
lower roll is fixed, while the upper roll may be adjusted to pro-
vide for the production of metal of various thicknesses. The
chief roller becomes very proficient in setting the machines for
rolling any gage of metal and is able to obtain very quickly the
required adjustment. The setting is made by adjusting the
rolls and testing the thickness of steel passed between them with
a micrometer; then, if necessary, further adjustment is made
until the desired result is obtained.

On the entering side of the mill there is a frame which supports
an emery cloth wiper through which the steel runs in order to

remove all foreign matter which might result in damaging the rolls. The mills are set to run in opposite directions, and arranged in series so that successive passes of the metal may be made through adjacent machines until the desired reduction has been obtained. The rolls are lubricated with a special grade of oil known as "roll oil," which is of about the same consistency as cylinder oil, but very carefully compounded to be sure that it is neither acid nor alkaline, as either condition would spoil the
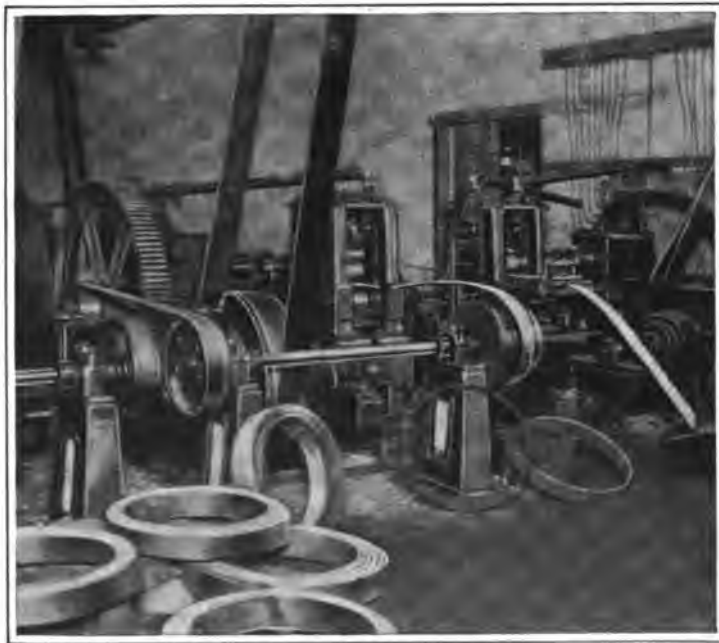
Fig. 18. Rolling Strip Steel — First Pass is made through Mill in Background, and Second Pass, through Front Mill

"bright" finish of the cold-rolled steel. After each two passes through the mill, the steel must be sent back to the annealing furnaces in order to remove strains which have been introduced through the mechanical working. What is known as "soft" steel is subjected to a final annealing operation after it has been rolled to the required thickness. The "half hard" stock receives one final pass through the rolls after being annealed. The

"hard" stock receives two passes through the rolling mill after the last annealing operation has been performed.

Reduction of Stock by Rolling. — The amount of reduction which can be obtained for each pass through the rolling mills depends upon the analysis of the steel; with low-carbon steel the reduction may be as great as 0.022 inch for each pass, and this will be gradually decreased until the final pass will only reduce the thickness of the metal about 0.005 inch. In the case of high-carbon stock, the reduction at each pass through the mill is much less; during the preliminary passes, this will amount to not more than 0.010 inch for each pass, while the reduction will be gradually decreased until the final pass reduces the thickness of the metal by only 0.003 inch. The degree of accuracy obtained in the gage of the metal is very great; in the thicker gages the variation will not exceed 0.0015 inch, while in the thinnest gages the limit of error is reduced to 0.00025 inch.

Trimming the Edges and Slitting Stock. — After the rolling operation has been completed, the subsequent treatment of the cold-rolled steel will depend upon the use for which it is intended. For some purposes it is merely necessary to trim the edges so that the stock is of uniform width, while in other instances these edges must be finished in such a way that they are made quite smooth. Then, for some uses, the steel must be hardened and tempered, while other purchasers require it to be "dead soft." Some customers of the cold-rolled steel-maker specify steel with a high polish, and others are not particular about this point. As all of these features are important in cold-rolled steel manufacture, they will be described in the order in which the successive operations are performed.

For trimming the edges of the steel to reduce it to uniform width, use is made of a rolling mill fitted with rotary shear blades which are set at the required distance apart. The steel is passed through these blades from a reel on which the coil is supported; and after being reduced to standard width, it is rolled up on another reel at the opposite side of the mill. At the same time, a second reel winds up the trimming from the edges of the stock, and this scrap is pressed into bales and re-

turned to the mill where the hot-rolled steel stock was produced. The same form of rotary shear is employed for slitting steel when it is desired to reduce stock of one width into two or more strips of lesser widths. The arrangement will be readily understood by referring to Fig. 19, which shows a mill set up for trimming the edges of the stock and slitting it into two narrow strips.

Finishing Edges of Stock. — When the edges of the strip steel must have a smooth finish, use is made of a simple but ingenious multiple filing machine which provides for producing a
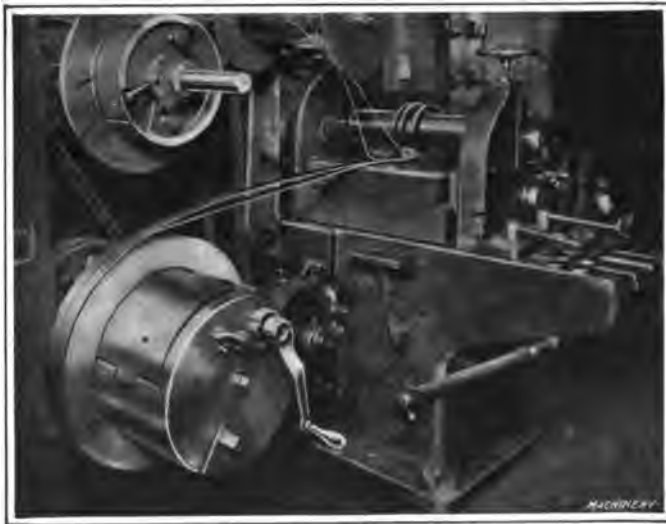
Fig. 19. Splitting Wide Strip into Two Narrow Strips and Trimming Edges — Note how Scrap is wound up on Upper Reel

smooth edge which may be either square or round. This machine consists of a table which supports a series of cross-slides made of wood that are grooved at both sides to receive tongues secured to the table. The ends of these slides are provided with short pieces of flat files, and the slides at opposite sides of the table are fitted with springs which tend to draw them together. In operation, the coil of strip steel, supported by a reel at one end of the table, is drawn between this series of files and is then wound on a reel at the opposite end. It will be evident that, in passing between the files, the edges of the steel are smoothed down;

and by having all the files perpendicular to the plane of the steel a square edge is imparted, while arranging the files at a variety of different angles results in rounding the edges of the stock.

Cutting Strips into Stock Lengths. — After the edges of the cold-rolled steel have been trimmed — and finished in cases where this operation is necessary — some of the strip steel is cut up into standard stock lengths. For this purpose a measuring bench and shear are used. The coil of steel is mounted on a reel and the steel is pulled between the shear blades so that a piece of the required length may be cut off, the length being indicated by a scale marked on the bench for that purpose. With this machine, one man and a helper can very rapidly cut up steel into any lengths which may be required.

Hardening and Tempering. — Purchasers of cold-rolled steel who use the material for making springs, and for various other purposes, specify steel which has been tempered; and for this purpose the cold-rolled steel-maker must provide his mill with equipment for doing this work. One successful method of heat-treatment is applied as follows: The steel in the form of a coil is mounted on a reel and connected with a "leader" which provides for drawing it through the heating and quenching mediums at the proper speed. The steel is first run through a lead bath and its temperature raised to about 1450 degrees F., according to the analysis of the steel, after which it is quenched in oil; then the steel passes on through a second lead bath which provides for drawing the temperature at from 780 to 800 degrees F., after which the metal is wound on a second reel. A variable-speed motor is used for drawing the steel through the furnace, and this motor transmits power through a series of herringbone reduction gears which provide for drawing the steel through at exactly the proper speed.

When the steel has been tempered, it passes onto the reels shown in Fig. 20, upon which the coils of steel are wound. It will be evident from this illustration that provision is made for heat-treating eight coils of steel simultaneously. All the reels shown are driven from a single motor, power being transmitted through a train of high-reduction herringbone gears which pro-

vide for drawing the steel through the hardening and tempering baths at the proper speed.

The preceding description applies to the method of heating the thicker gages of steel; in the case of the thinner gages, exactly the same method and form of equipment are employed, except that the metal is quenched in a lead bath which is kept just above the melting point, i.e., at about 630 degrees F. This results in making the steel practically "glass hard." The object of quenching the thin steel in a lead bath is that it avoids
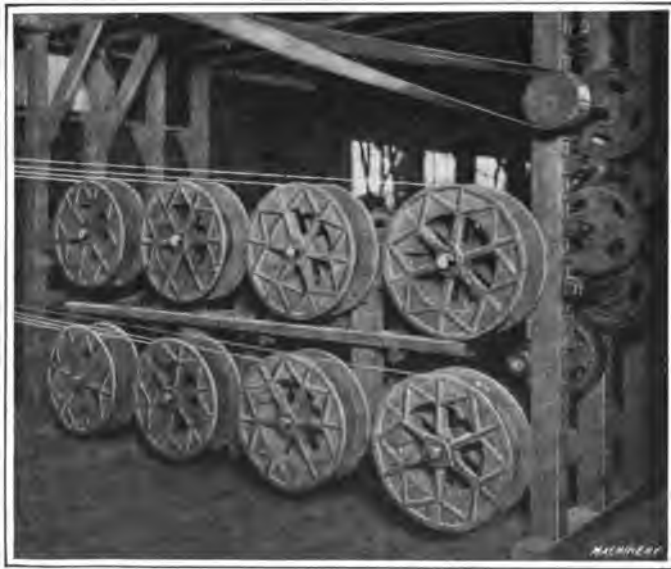
Fig. 20. Reels on which Strip Steel is wound after Heat-treating Operation is completed

the tendency to crack and become very crooked, which is a constant source of trouble where the steel is hardened in oil.

Polishing Cold-rolled Steel. — For certain purposes, there is a demand for cold-rolled steel with a high polish, and to meet the requirements of such users, the steel is taken from the hardening and tempering department and subjected to a polishing treatment. This is done on machines provided with a series of rolls over which the steel runs, one of these machines being shown in Fig. 21. Upon entering, it passes through a box

containing moist emery powder which must be extremely fine, powder from No. 80 to No. 100 being generally used. The steel carries away some of this emery with it, and in passing over the basswood rolls, a rubbing action takes place which imparts a high polish to the steel. Upon leaving the machine, the metal passes between a series of wipers which effectually remove any emery which is left on the metal.

Cold-rolled strip steel is made by the Schwartz-Herrmann

Fig. 21. Special Polishing Machine designed for Applying High Finish to Strip Steel

Steel Co. in widths ranging from $\frac{3}{8}$ up to $4\frac{3}{16}$ inches; and the thickness of the product covers a range from 0.003 to 0.083 inch. On the thicker gages, the steel is guaranteed to come within 0.0015 inch of the specified thickness; and this limit of error is gradually reduced, so that it is possible to furnish the thinnest stock with a guarantee that the error in thickness does not amount to more than 0.00025 inch. To any experienced mechanic, it will at once be apparent that the possibility of securing such a high degree of accuracy can only result through exercising

absolute care in carrying out every step of the process of manufacture.

Wire Drawing. — After wire rods have been rolled down to the smallest practicable size, smaller diameters are produced by means of drawing the wire rod through a plate or die provided with a hole which reduces the size to the desired diameter. Wire drawing has been practiced for centuries along lines very similar to those still employed. It is definitely known that there was a wire drawing mill in Nuremberg, Germany, in 1370. The first wire drawing mill in America was built in 1775 in Norwich, Conn.

Iron and steel wire is generally drawn from No. 5 rod, which is 0.207 inch in diameter. The rods are wound on reels, as mentioned in the preceding paragraphs, into coils weighing from 150 to 300 pounds. The rods, as delivered by the rolling mill, are covered with scale, and the first process, therefore, is to place the wire rod coils for a short time in a pickling bath of dilute sulphuric acid, heated to a boiling heat by steam coils. This solution loosens the scale which is then washed off with a stream of water. The bundles are next dipped in a limewater solution and are then placed in a "dry house" or "baker," where they are subjected to a temperature of from 300 to 400 degrees F. for several hours. A thin coat of the limewater solution adheres to the rods and lubricates the wire as it passes through the dies. If the wire rod is not thoroughly freed of the scale, or is not thoroughly covered with lime, the die hole will be quickly worn larger than the correct size, and the wire will be scratched, out of round, or of increasing gage. If the wire rod is left in the sulphuric-acid solution too long, it becomes brittle and the surface is hardened. The wire rod also becomes brittle if removed from the dry house too soon. Brittleness may be removed, however, by leaving the rods in the dry house longer than would otherwise be necessary.

Wire-drawing Machines. — Briefly described, the machines used for wire drawing consist of a die or drawplate provided with holes through which the wire is drawn, and means for pulling the wire through these dies and winding it upon a reel. The

wire-drawing machines may be either of the single-block or
continuous types. A single-block machine is shown in Fig. 22.
It consists mainly of a table T to which is fastened a bracket B,
which holds the die or drawplate, and a power-driven vertical
drum or block D on which, as it rotates, the wire is wound after
having been pulled through the die. Before the drawing can
begin, the wire is pointed so that the operator can push the end
of it through the drawplate. The pointing is done in a special
pointing machine. After that, the wire is pushed through that
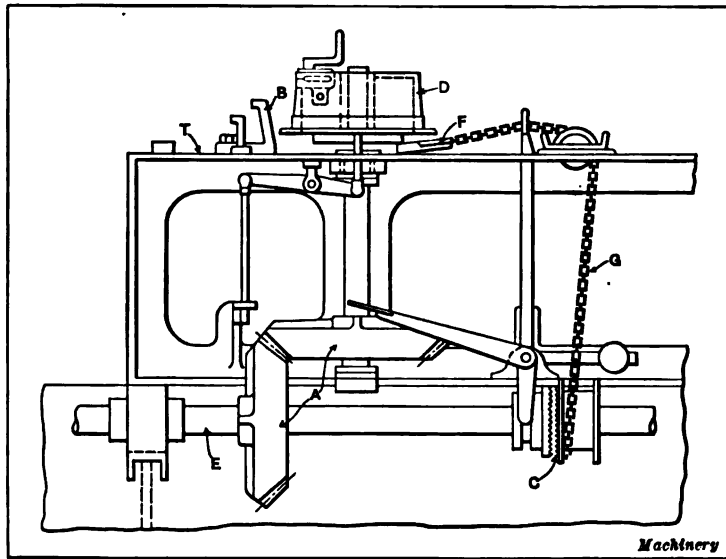
Fig. 22.   Single-block Wire-drawing Machine

hole in the drawplate which is of the correct diameter to which
the wire is to be reduced, and then pulled through this hole, by
power, by means of tongs F, a chain G, and a clutch C, for a
distance of about two or three feet. Then the end of the wire is
attached to the block D, upon which the drawn wire will be
wound, and the block is set in motion by means of bevel gearing
A and shaft E. The wire will thus be pulled through the draw-
plate and reduced to the required diameter. The block is
slightly tapered so that the coil of wire can be easily removed
from it when completed. Continuous wire-drawing machines

have a series of dies through which the wire passes. Between each two dies, the wire is wound over pulleys or blocks, as otherwise it would be impossible to pull the wire through successive dies. The speed at which wire drawing is done varies according to the material and the amount of reduction. As an average, it varies from 60 feet per minute for slow speeds in single-block machines to 900 feet per minute with the high speeds possible in continuous machines.

When drawing, the wire is lubricated, oil, tallow, and soap water being used for this purpose. Smaller sizes, especially of music wire, are drawn wet or very thoroughly lubricated, the reels of wire, in this case, being set into tubs containing the lubricating solution of soap water, and drawn directly from the submerged reels through the drawplate. The wire is reduced in diameter for each drawing or pass by one number on the standard wire gage scale. When the wire is drawn through the holes in the dies, thus reducing its diameter, its surface becomes hard and brittle, and the wire is, therefore, annealed at frequent intervals before it is reduced to a smaller size by a subsequent drawing operation.

Drawplates. — The drawplate or die for larger sizes of wire is generally made from chilled cast iron or tool steel, or from a high-grade tungsten steel into which a number of holes of different sizes are drilled and reamed. The holes taper, having the correct diameter of the wire to be drawn at that face of the drawplate which is towards the block or pulley. For smaller sizes of wire, the dies are made from less expensive or imperfect varieties of diamonds, and are known as "diamond dies." Generally speaking, wire drawn to not less than 0.040 inch in diameter is drawn through chilled cast-iron or tungsten steel drawplates, while wire of from 0.040 down to 0.002 inch in diameter, which is the smallest commercial size ordinarily drawn, is produced by diamond dies inserted in a brass body. The large sizes of wire are more often drawn on single-block machines, while the smaller sizes are drawn on continuous machines. The size of diamond for wire 0.040 inch in diameter is about 3 or 3½ carats, while ½-carat stones will suffice for dies for drawing wire 0.010 inch in

diameter. The life of the diamond die used for drawing steel wire averages only about three days. The life depends solely upon the length of wire passed through it; the speed at which the wire is drawn appears to have little effect on it. About 200 pounds of steel wire can be drawn through a No. 32 Brown & Sharpe gage diamond die before its size is too large for further use; but only 15 pounds of wire can be drawn through holes of from 0.003 to 0.005 inch in diameter, and less than one pound can be drawn through holes smaller than 0.002 inch. When the diamond dies are worn too much, they are re-drilled for a larger gage number. In drilling the diamonds, the average time for enlarging a hole 0.001 inch in diameter is about 1½ hour. For hard music wire, diamonds of comparatively large size are required; thus for holes as small as 0.005 inch in diameter, 2- to 2½-carat diamonds are used.

Annealing the Wire. — Wire is drawn cold, that is, the metal is at ordinary temperatures; this gives a bright finish and renders polishing unnecessary. The repeated drawings through the dies increase the ultimate strength, but lessen the ductility in almost the same ratio. In this condition, the wire is known as "hard-drawn." Because of this loss of ductility, metal that is to be drawn through several dies before it becomes of the desired size must be annealed. The annealing may be done by placing the bundles of wire in a muffle furnace, or in large iron or steel cylindrical pots which are hermetically sealed and heated by coal fires. Care must be taken that the wire is thoroughly and uniformly annealed. In the case of steel wire, it is also necessary to see that the steel is not burnt or overheated. While annealing restores the ductility of the wire, it reduces the ultimate strength. It is generally necessary to anneal wire after it has been drawn through three or four dies.

In the so-called "patent process," the wire is passed through a long furnace in which it is heated to approximately 1800 degrees F. As it emerges from this, it is cooled by the air. Sometimes the wire issuing from this furnace is passed through a lead bath that is maintained at a temperature of from 800 to 900 degrees F. The wire in either case has the best working

combination of tensile strength and toughness obtainable and may be given greater "drafts," or reductions, in the die than wire annealed in the ordinary manner.

Wire Gages. — The size of wire is generally indicated by gage numbers. There is a great multiplicity of different wire gages in use. Upon the recommendation of the Bureau of Standards at Washington, a number of the principal wire manufacturers and consumers have, however, agreed to designate the American Steel & Wire Co.'s gage, which is the same as the Washburn & Moen and the Roebling gage, as the "Steel Wire Gage" or the "U. S. Steel Wire Gage"; hence, this gage may be considered standard for steel wire in the United States. For copper wire and wires of other metals, the "American Wire Gage," which is also known as the "Brown & Sharpe Gage," is standard. For music or piano wire, the gage known as "American Steel & Wire Co.'s Music Wire Gage" is adopted as standard in the United States upon the recommendation of the United States Bureau of Standards. The standard wire gage in Great Britain is that known as "British Standard Wire Gage," also known as "New British Standard," the "English Legal Standard," and the "Imperial Wire Gage."

The Birmingham or Stubs iron wire gage is now nearly obsolete and is little used, either in Great Britain or the United States. Stubs steel wire gage, used for drill rod, however, is still extensively used. Tables of these various wire gages will be found in all standard engineering handbooks.

CHAPTER XI

STRUCTURAL CARBON AND ALLOY STEELS

STEEL may be divided into two large general classes, according to the use to which it is put; these are known as *tool steel* and *structural steel*. The former class, in its widest sense, includes all those steels that are used for cutting tools, while the latter class includes those steels that are mainly used in the making of machinery and the building of structures. Applied in this sense, structural steel includes both carbon steels and alloy steels used in machine construction, bridges, etc.

Structural Carbon Steel. — The carbon steel used for structural purposes contains a smaller amount of carbon than that used for tool steel, and is generally referred to as "low-carbon" or "medium-carbon" steel. It is generally made either by the Bessemer or the open-hearth process. The term "structural steel" is also used in a narrower sense, referring only to the steel used for the construction of buildings, bridges, etc. The properties and requirements of steel of this kind are dealt with in the closing paragraphs of Chapters VII and VIII, on Bessemer steel and open-hearth steel, respectively. The carbon steel dealt with in this chapter will be that mainly used in machine construction, which may also be made either by the Bessemer or the open-hearth processes, and which may or may not be heat-treated to increase the strength or toughness, or casehardened to increase the resistance to wear, after it has been machined to the proper shape required for the machine for which it is intended.

Carbon steels for structural purposes are made with carbon contents varying all the way from 0.10 to 1.00 per cent. That containing 0.10 per cent of carbon is usually known by the trade name "soft basic open-hearth steel." The 0.20-per-cent car-

bon steel is generally known as "machine steel." Steels containing 0.30, 0.40, and 0.50 per cent of carbon are also made for structural purposes. Steel with a higher carbon content than this is seldom used as a structural steel, except steel containing from 0.80 to 1.00 per cent of carbon, which is known as "spring steel," and is generally used for springs. The heat-treatment to which the carbon steels containing from 0.20 to 0.25 per cent of carbon are generally subjected, when these steels are employed for parts exposed to wear, is known as "casehardening."

Casehardening. — Casehardening is a process for hardening the surface of low-carbon steel. High-carbon steel will harden by being heated to a certain temperature and suddenly quenched in water, brine, or oil. Low-carbon steel will not harden appreciably if treated in this manner, and the process of casehardening, therefore, consists in first increasing the carbon content of the surface of the low-carbon steel so that it can be hardened by being quenched. The surface, or *case*, only will be high enough in carbon to be hardened, and the interior, or the *core*, will still be low in carbon and soft. Small machine parts are generally casehardened in quantity, the process being briefly as follows: The parts are packed in cast-iron or welded sheet-steel boxes, together with some material containing carbon such as charcoal, charred leather, powdered bone, etc. The low-carbon steel will absorb carbon on its surface from this material, when the box and its contents are heated to a temperature of from 1600 to 1800 degrees F. for a certain length of time, depending upon the depth of hardened surface desired and the nature of the material. The absorption of carbon begins when the steel reaches about 1300 degrees F., but commercially carburizing must be done at a higher temperature. The length of time at which the steel should be held at the carburizing temperature after the required degree of heat has been reached may vary from two to six hours. At the end of the carburizing period, the box is withdrawn from the furnace and allowed to cool slowly. The articles are then taken out of the carburizing mixture, placed in a muffle furnace, and reheated to about 1500 degrees F., after which they are quenched in water or oil. For

ordinary purposes, clear cold water is satisfactory. Salt water or brine is used when a very hard surface is desired, and the oil bath when a hard surface is not as important as a tough core.

The method of casehardening just described is probably the most common method, but when a hard case is the only re- quirement, the articles may be quenched directly after car- burizing by emptying the contents of the casehardening boxes directly into cold water or oil, but in this way both the core and the case are coarsely crystallized and the strength is reduced. Allowing the box and its contents to cool and then reheating, prior to quenching, gives more satisfactory results than when the parts are dumped directly into the quenching bath at the end of the carburizing period.

When it is desired to increase the toughness and the strength of the casehardened article and refine the case as well, it should be subjected to a double reheating after carburizing; that is, it should first be carburized and permitted to cool slowly in the carburizing mixture, then reheated to about 1500 degrees F. and quenched in water or oil, and again reheated to about 1400 degrees F. and quenched in water or oil. Finally, the temper is drawn in oil at any temperature varying from 300 to 450 degrees F. according to the hardness desired.

Instead of packing the material to be casehardened in a car- bonaceous mixture, casehardening is now also done by placing the articles to be carburized in a revolving drum or retort through which a current of carbonaceous gas is forced. The retort serves as a muffle and is surrounded by the flames of the heating gases. It is claimed that by gas carburizing, small pieces can be car- burized much more quickly and at about one-half the cost as compared with packing in iron boxes and heating. Carbon monoxide has been found to be a suitable gas for gas carburizing, except that it has an oxidizing effect that might spoil small parts which cannot be ground afterwards. Another process has, therefore, been developed, in which the work is packed with wood charcoal in a cylinder and, when heated to the carbur- izing temperature, a current of carbon dioxide is injected into the cylinder.

Steels for Casehardening. — The percentage of carbon in steels ordinarily used for parts to be casehardened varies, as a general rule, from 0.15 to 0.25 per cent. For general work, steel of the following composition will be found satisfactory: Carbon from 0.15 to 0.20 per cent; manganese, less than 0.35 per cent; silicon, less than 0.30 per cent. The sulphur and phosphorus should be as low as possible. If the carbon exceeds 0.20 per cent, it tends to give a hard instead of a soft core. On the other hand, if the carbon content is too low, the steel may be difficult to machine; hence, steels containing as much as from 0.20 to 0.25 per cent of carbon are generally used.

Degree and Depth of Hardened Surface. — The percentage of carbon contained in the casehardened surface varies according to the requirements. For most purposes, 0.90 per cent of carbon is preferable. A case containing 1.10 per cent of carbon gives a very hard wearing surface that is suitable for work that must withstand a fairly constant pressure, as shafts running in bearings, etc.; but this amount of carbon will render parts that must withstand repeated shocks too brittle; for this work, the case should not contain more than from 0.90 to 1.00 per cent carbon.

The percentage of carbon in the hardened crust varies with the depth of the latter; therefore, the deeper the penetration, the higher must be the carbon content near the surface. Crusts about 0.050 inch deep usually have from 0.85 to 0.90 per cent of carbon on the surface. In many instances, a penetration of 0.04 inch is sufficient, but if the work is to be ground after casehardening it should be carburized to a depth of about 0.060 inch. Too deep a carburized case makes the work more brittle, partly because of the prolonged exposure to a high temperature and partly because of the increase in the hardened section and the decrease in the softer and more ductile core; hence, parts to withstand bending stresses, like gear teeth, should not be carburized too deeply. Carburization takes place rapidly until the crust is saturated with carbon (about 0.90 per cent of carbon marks the saturation point), when there is a sudden diminution in the rate of carburization, which varies according to the tem-

perature. The penetration of the carbon increases with the temperature and with the time of exposure, but not in direct proportion to these two factors.

Casehardening for Colors. — When desired, such parts as wrenches, etc., may be hardened and colored at the same time. The parts to be colored, however, must be well polished and must not be handled with greasy hands. For this purpose, the following mixture may be used: 10 parts of charred bone, 6 parts of wood charcoal, 4 parts of charred leather, and 1 part of powdered cyanide. The leather should be black, crisp, and well pulverized, and the four ingredients well mixed. The object in charring the bone and leather is to remove all grease. If the colors obtained are too gaudy, the cyanide may be omitted, and if there is still too much color, the charcoal may be left out. Another mixture consists of 10 parts of granulated bone, 2 parts of boneblack, and 1 part of granulated charred leather. The parts to be colored and hardened may be packed in a piece of gas pipe having a closed end. Pipe is preferable, because the pieces can be dumped into the cooling water with little or no exposure to the air. The work should then be heated to a dark cherry-red for about four or five hours; if the temperature is too high, no colors will appear. A compressed-air pipe should be connected with the water pipe to the cooling tank in such a way that a jet of air is forced upward, thus filling the tank with bubbles. There should also be a sieve or basket in the tank for receiving the work. After quenching, the parts should be placed in boiling water for five minutes and then buried in dry sawdust for half an hour.

Cleaning Work after Casehardening. — Work having crevices in which dirt is likely to stick after casehardening may be cleaned by washing in a solution of 1 part of caustic soda to 10 parts of water. In making this solution, the soda should be put into hot water gradually, and the mixture stirred until the soda is thoroughly dissolved. A more effective method is to place the work into a mixture of 1 part of sulphuric acid to 2 parts of water for about three minutes, and then wash immediately in a soda solution.

Properties and Uses of Structural Carbon Steel. — When in the following paragraphs the elastic limit per square inch and other properties of different kinds of steels are given, these refer to bars about one square inch in sectional area; where two figures are given for elastic limit or other properties, the high elastic limits can be obtained only on sections of this size, or smaller, with very careful heat-treatment, while the low elastic limits may be expected on heavier sections.

Carbon Steel with 0.10 per cent Carbon. — Steel with 0.10 per cent of carbon is commonly used for seamless tubing, pressed steel parts, etc. It is known in the trade as "soft basic open-hearth steel," and is particularly useful for the purposes mentioned, because it is soft and ductile, and can be drawn and shaped, to a great extent, without cracking. It should contain about 0.45 per cent of manganese; the contents of neither phosphorus nor sulphur should exceed 0.04 per cent. In its annealed condition, this steel has an elastic limit of from 30,000 to 35,000 pounds per square inch, with a reduction in area of from 55 to 65 per cent, and an elongation in two inches of from 30 to 40 per cent. It should not be used where a great deal of strength is required; but the quality of the material may be improved by cold-drawing; in its natural or annealed condition, it cannot be easily machined, as it is likely to tear when turned, threaded, or broached. Heat-treatment does not increase its strength, but does slightly increase its toughness. The only heat-treatment of any value is to heat the steel to about 1500 degrees F. and quench it in oil or water. It need not be drawn afterwards. It is not suitable for casehardening, although it may be casehardened to some extent, if required. If cold-drawn, and afterwards heated, it will return to the characteristics of the annealed material, the same as all materials the elastic limit of which have been increased by cold-working.

Carbon Steel with 0.20 per cent Carbon. — Steel with 0.20 per cent of carbon is generally known in the trade as "machine steel," and is used mainly for such machine parts as require casehardening after machining, as the steel is especially adapted for this process. This steel should contain about 0.65 per cent

of manganese, and the phosphorus and sulphur content should not exceed 0.04 per cent. It can be used the same as the 0.10-per-cent carbon steel for cold pressed shapes, and can be drawn into tubes and rolled into cold-rolled forms. It is especially used for forged and machined casehardened parts, as it forges and machines well, but it is not used when great strength is required. When in its annealed condition, it has an elastic limit of from 30,000 to 40,000 pounds per square inch, a reduction in area of from 45 to 60 per cent, and an elongation in 2 inches of from 25 to 35 per cent. When heat-treated, the elastic limit can be increased to from 40,000 to 75,000 pounds per square inch, but the reduction in area is changed to from 15 to 50 per cent, and the elongation in two inches to from 15 to 30 per cent.

This steel may be casehardened in two ways. Parts which are not subjected to heavy load or shocks, but simply must have a hard surface, may be heat-treated as follows: Carburize at a temperature of from 1600 to 1700 degrees F. and cool slowly, or quench in oil. Then reheat to from 1450 to 1500 degrees F. and quench in oil. Parts which must not only be hard on the surface, but which should also have considerable strength, as, for example, gears, should have a double heat-treatment as follows: Carburize at a temperature of from 1600 to 1700 degrees F. and cool slowly in the carburizing packing material. Then reheat to from 1500 to 1550 degrees F. and quench in oil, and reheat for a second time to from 1400 to 1450 degrees F., and quench in oil. Finally, draw in hot oil to a temperature of from 300 to 450 degrees F., according to the degree of hardness required. The heat-treatment does not increase the ultimate strength in any appreciable degree, but, because of the refinement of the grain, it increases the elastic limit.

Carbon Steel for Screw Machine Work. — Steel suitable for screw machine work is generally known as "screw stock," and contains generally from 0.18 to 0.25 per cent of carbon. It should contain from 0.30 to 0.80 per cent of manganese; not over 0.12 per cent of phosphorus; and from 0.06 to 0.12 per cent of sulphur. Machine parts requiring great strength and toughness cannot be made from this material, and most small parts

made from it, such as screws, etc., should be heat-treated, the heat-treatment consisting of heating to 1500 degrees F. and quenching in oil or water; then reheating to from 600 to 1300 degrees F. and permitting the steel parts to cool down slowly. The material may also be casehardened in about the same way that the regular 0.20-per-cent carbon steel is casehardened. Screw stock is made either in the form of cold-rolled or hot-rolled bars. Cold-rolled bars are much stronger and may sometimes be used without heat-treatment; but hot-rolled screw stock should always be heat-treated.

Carbon Steel with 0.30 per cent Carbon. — Steel containing 0.30 per cent of carbon is used in machine construction for axles, shafts, and other structural parts which require strength as well as toughness. This steel is heat-treated to increase its elastic limit, but is not generally used for casehardening purposes, although it may be casehardened, if required. It can easily be forged and machined. This steel should have the same composition with regard to manganese, phosphorus, and sulphur as the 0.20-per-cent carbon steel. In its annealed state, it has a strength of from 35,000 to 45,000 pounds per square inch, a reduction in area of from 40 to 55 per cent, and an elongation in two inches of from 20 to 30 per cent. In its heat-treated condition, it has an elastic limit of from 40,000 to 80,000 pounds per square inch, with a reduction in area and elongation practically the same as in the annealed condition.

This steel may be subjected to either a single or double reheating. The heat-treatment in the first case consists of heating to about 1500 degrees F. and quenching in oil or water, and reheating to from 600 to 1200 degrees F., and permitting the metal to slowly cool. The double reheating heat-treatment consists of heating the steel to from 1500 to 1550 degrees F., quenching in oil or water; reheating to from 1400 to 1450 degrees F., and again quenching; after which the steel is again reheated to from 600 to 1200 degrees F. and slowly cooled. When used for casehardening, the steel should be heat-treated in the same way as in the double reheating process, but, in addition, should be drawn in oil to a temperature of from 300 to 450 degrees F.

Carbon Steel with 0.40 per cent Carbon. — Steel containing 0.40 per cent of carbon is used for such machine parts as require a high degree of strength and toughness. In automobiles, for example, it is used for crankshafts and driving shafts. It has also been used for automobile transmission gears, but is not quite suitable for this purpose, because it is not hard enough without casehardening, and, when casehardened, does not possess enough toughness. The manganese, phosphorus, and sulphur content should be about the same as that in the 0.20-per-cent carbon. In its annealed condition, its elastic limit varies from 40,000 to 50,000 pounds per square inch; the reduction in area, from 40 to 50 per cent; and the elongation in two inches, from 20 to 25 per cent. When heat-treated, the elastic limit varies from 45,000 to 100,000 pounds per square inch; the reduction in area, from 25 to 50 per cent; and the elongation in two inches, from 5 to 25 per cent. When annealed, this steel can be easily machined, but is not suitable for automatic screw machine work. When heat-treated, it should be subjected to a double reheating. It should first be heated to from 1500 to 1550 degrees F. and slowly cooled. It is then reheated to from 1400 to 1450 degrees F. and quenched in oil or water, and finally reheated to from 600 to 1200 degrees F. and slowly cooled.

Carbon Steel with 0.50 per cent Carbon. — Except for the increased carbon content, this steel has the same composition as the 0.20-per-cent carbon steel. In its annealed condition, it has an elastic limit varying from 45,000 to 60,000 pounds per square inch; a reduction in area, from 30 to 40 per cent; and an elongation in two inches, of from 15 to 20 per cent. When heat-treated, its elastic limit is raised to from 50,000 to 110,000 pounds per square inch, but the reduction in area and the elongation are generally decreased. It should be subjected to the same heat-treatment as the 0.40-per-cent carbon steel. It is somewhat more difficult to machine than the steels with a lower carbon content, but is generally used for the same purposes as the 0.40-per-cent carbon steel.

Spring Steel. — The steel generally known as "spring steel" contains from 0.80 to 1.00 per cent of carbon. These steels are

always used in a heat-treated condition, and have, when heat-treated, an elastic limit of from 90,000 to 160,000 pounds per square inch. The 0.80-per-cent carbon steel is generally used for springs of light section. Its composition, in addition to the carbon, should be about 0.35 per cent of manganese and not more than 0.04 per cent of either phosphorus or sulphur. The heat-treatment of the spring after shaping or coiling consists in heating to from 1425 to 1475 degrees F., and quenching in oil, after which the spring is reheated to from 400 to 800 degrees F., according to the degree of temper desired. Steel containing from 0.95 to 1.00 per cent of carbon is used considerably for the heavier types of springs. It is heat-treated in a manner similar to that used in the 0.80-per-cent carbon steel, but the first heating, previous to quenching in oil, should be at a temperature slightly less than that used for the 0.80-per-cent carbon steel.

The Pennsylvania Railroad specifications for spring steel require a carbon content not under 0.90 per cent; manganese, from 0.25 to 0.50 per cent; silicon, not over 0.10 per cent; phosphorus, 0.05 per cent, but not over 0.07 per cent; and sulphur, not over 0.03 per cent.

The United States Navy Department specifies that spring steel must be made either by the open-hearth, crucible, or electric process. The carbon content must vary between 0.70 and 1.10 per cent; the manganese, between 0.25 and 0.50 per cent; the silicon content must not exceed 0.25 per cent; and that of sulphur and phosphorus must not exceed 0.04 per cent. The ultimate tensile strength, after heat-treatment, must be at least 180,000 pounds per square inch and the elastic limit must be at least 75 per cent of the ultimate tensile strength. The following tests are prescribed: A heat-treated bar, resting on supports 24 inches between centers, must not take a permanent set of more than 0.050 inch after the first application of a load which will produce a fiber stress of 135,000 pounds per square inch. When a load which will produce a fiber stress of 160,000 pounds per square inch is applied, the permanent set must not be more than 7.5 per cent of the total deflection, and after five

additional applications of a load producing a fiber stress of 150,000 pounds per square inch, there must be no further set. With regard to the variation in size of bars of spring steel, the Navy Department has issued the following regulations: In round bars, a variation of 0.020 inch in diameter is allowable; in rectangular bars, a variation of 0.020 inch in thickness and 0.030 inch in width, from the sizes ordered, will be permitted. These specifications do not apply to drawn, round, or square wire below $\frac{1}{16}$ inch in diameter or size, nor to flat bars below $\frac{1}{16}$ inch thick.

Structural Alloy Steels. — The term " alloy steel " is applied to steels which contain some metallic element other than iron, which gives to them peculiar or characteristic properties. The metals added to steel to form alloy steels are chromium, cobalt, manganese, molybdenum, nickel, titanium, tungsten, vanadium, and uranium. Of these the alloys with chromium, manganese, nickel, titanium, and vanadium are structural steels, while the alloys with cobalt, molybdenum, tungsten, and uranium are used for cutting tools; that is, they are tool steels of the "high-speed steel" class. Some of the latter steels also contain chromium and vanadium. In addition to the alloy steels composed mainly of one metallic element outside of iron, there are alloy steels consisting of two or even three metallic elements besides iron. The most common of the structural steels thus composed are chrome-nickel or nickel chromium steel, and chrome-vanadium steel. Only the structural steels will be dealt with in this chapter, the high-speed steels being treated in Chapter XII.

Alloy steels have become extensively used during the last decade and are likely to displace structural carbon steels for important structural purposes, where a decrease in weight for equal strength is of importance, as in the construction of automobiles, bridges, ships, etc. It is, however, only possible to obtain the increased strength in alloy steels by proper heat-treatment. In their annealed state they are not much superior to ordinary carbon steel. The heat-treatment of alloy steels, therefore, is one of the most important branches of the industries making use of this material. Alloy steels may be made by the open-hearth, crucible, or electric process.

Chromium Steel. — Alloy steels containing only chromium as the alloying metal are not used to any great extent for structural purposes, as chromium is generally not used alone, but in combination either with nickel or with vanadium. There are few purposes, however, for which a chromium steel is used without other metallic additions, as, for example, for armor-piercing projectiles, for which it is extensively used. It is also employed in rock-crushing machinery and in the construction of safes, where alternate layers of soft wrought iron and chromium steel are employed. Chromium is usually present in chromium alloy steels in amounts from 2 to 5 per cent, the percentage of carbon varying from 0.8 to 2 per cent. The properties brought out by heat-treatment in this steel are an intense hardness combined with a very high elastic limit, so that the metal is peculiarly adapted to withstand violent shocks.

Manganese Steel. — Manganese steel, also known as Hadfield's steel on account of having first been produced by the Hadfield firm in England, is composed of from 11 to 14 per cent of manganese; from 1.0 to 1.3 per cent of carbon; from 0.3 to 0.8 per cent of silicon; and from 0.05 to 0.08 per cent of phosphorus. The sulphur content should be so low as to be negligible, as it is eliminated in making the steel by the manganese forming a sulphide which rises to the surface and enters the slag. There are manganese steels having different compositions from that mentioned above, but the steel having the composition given is that commercially known as "manganese steel." If there should be only about 1.5 per cent of manganese, the steel will be very brittle and this brittleness increases until the manganese content reaches about 5 per cent, when the brittleness is so extreme that the steel can be pulverized under a hammer. Greater percentages of manganese, however, make the steel ductile and hard and a manganese content of about 12 per cent brings out these qualities to the best advantage. Manganese steel is melted and cast in molds. After having been cast, it is subjected to a heat-treatment consisting of heating the steel to about 1900 degrees F. and then cooling it as quickly as possible by immersing in cold water. The more sudden the cooling the

better. The average commercial manganese steel when heat-treated has a tensile strength of from 80,000 to 90,000 pounds per square inch, an elastic limit of from 45,000 to 60,000 pounds per square inch, and an elongation of about 30 per cent. The Hadfield firm in England, however, has produced rolled manganese steel having a tensile strength of 150,000 pounds per square inch, an elongation of 50 per cent, and a reduction of area of nearly 40 per cent. The elastic limit of this steel, however, was only about 56,000 pounds per square inch. Manganese steel has the peculiar property of being practically non-magnetic and hence is used for purposes which require a hard non-magnetic metal.

The rolling and forging of manganese steel proved a difficult operation for many years, and it was not used except in its cast form. At present, however, large ingots are rolled into rails and other shapes. The heat-treatment of the rolled steel is similar to that of the cast material. It is extremely difficult to machine and, as a rule, is finished by grinding. It is used mostly for castings subjected to heavy strains and especially to excessive wear, such as the wearing parts of steam shovels, rock crushers, ore crushers, and other mining machinery. It is also used in the making of safes, and to a limited extent for rails, frogs, and crossings, but the steel is expensive and only where it cuts down a high maintenance cost is its use economical. It is stated that, for screening coke when woven screens of manganese steel bars are used, their life is a hundred times as great as that of screens made of the soft carbon steel generally used.

Manganese steel has a very low conductivity for both heat and electricity, a low melting point (about 2480 degrees F.) and a very high coefficient of expansion. When cast, it is brittle, and, after heat-treatment, its tensile strength is only moderate, with a low elastic limit in both tension and compression and a rather high ductility; its shearing strength is remarkably high. When rolled or forged and heat-treated, the tensile strength of manganese steel is increased greatly, and the ductility is much improved. The rolled material, if not heat-treated, is quite brittle.

The ductility of the metal is increased by quenching, which is entirely opposite to the result that would be obtained with carbon steels. While manganese steel is so hard that no steel tool can cut it, castings and forgings made of it may be bent and hammered like mild steel. The chief characteristic of manganese steel is its extreme hardness, because of which it cannot be machined. Owing to the low elastic limit, the metal can be made to pean, or flow, when cold, by hammering. The tendency of the steel to flow under heavy loads prevents its being used for railway car wheels. It is, however, widely used under light loads in mine and quarry cars, blast-furnace charging buggies, etc. In a way, therefore, the steel is soft, and hardness tests that depend upon indenting the material do not give high figures; yet its resistance to most kinds of wear is extraordinarily great.

The simplest and cheapest way to produce manganese steel is to blow in the Bessemer converter molten 80-per-cent ferromanganese and molten soft steel containing from 0.10 to 0.25 per cent of carbon. The carbon content of the ferromanganese brings up the steel to the correct composition as regards carbon. A manganese steel recently placed on the market contains only from 6 to 9 per cent of manganese, yet it is said to possess the characteristic hardness and ductility of steel having a higher manganese content. Its composition is based on the theory that a certain relation exists between the percentage of the manganese and the percentage of the carbon employed with it in the steel, and that the proportioning of the carbon ingredients in accordance with this relation gives a steel with the desired characteristics. This steel is made in the usual manner; it is a poor conductor of heat and is practically nonmagnetic.

Nickel Steel. — Nickel steel is one of the most important of the structural alloy steels. The most common grades contain from 3 to 5 per cent of nickel and from 0.10 to 0.50 per cent of carbon. The steel most generally used contains 3.5 per cent of nickel, but the carbon content varies by 0.05 per cent all the way from 0.15 to 0.50 per cent of carbon, according to the purpose for which the steel is intended. Generally speaking, when nickel steel is properly heat-treated, it combines great tensile strength

and hardness with a high elastic limit and ductility. For this reason, it has been used for armor plate, because it does not crack when perforated by a projectile. It is largely used in automobile construction and has been employed in bridge construction and for rails and ammunition. Nickel steel rails resist abrasion better than ordinary Bessemer or open-hearth rails — so much so in fact that it has been claimed that one nickel-steel rail will outlast four Bessemer rails. It is also used for marine shafting where its strength and ductility make it valuable on account of the high and sudden stresses that are frequently imposed on propeller shafts.

The Society of Automobile Engineers (now the Society of Automotive Engineers) prescribes in a report of January, 1912, that 3.50-per-cent nickel steel shall contain, in addition to its carbon content, from 0.50 to 0.80 per cent of manganese, and not more than 0.04 per cent of either phosphorus or sulphur. The properties of nickel steel depend, in addition to its nickel content, upon the carbon percentage; 0.15-per-cent carbon nickel steel in its annealed condition will have an elastic limit of from 35,000 to 45,000 pounds per square inch and, in its heat-treated condition, an elastic limit of from 40,000 to 80,000 pounds per square inch. The 0.30-per-cent carbon nickel steel in its annealed condition has an elastic limit of from 45,000 to 55,000 pounds per square inch, and, when heat-treated, an elastic limit of from 65,000 to 150,000 pounds per square inch; while the 0.50-per-cent carbon nickel steel, annealed, has an elastic limit of from 55,000 to 70,000 pounds per square inch, and, heat-treated, an elastic limit of from 70,000 to 200,000 pounds per square inch. The elongation in two inches varies from 25 to 35 per cent in the annealed 0.15-per-cent carbon nickel steel to from 15 to 25 per cent in the annealed 0.50-per-cent steel; the elongation of the heat-treated steel varies from 15 to 35 per cent in the 0.15-per-cent carbon nickel steel, and from 5 to 20 per cent in the 0.50-per-cent steel.

All nickel steel may be heat-treated either by a single or double heat-treatment. In the first case, it is heated to from 1500 to 1550 degrees F. and quenched in oil and water, and then

reheated to from 600 to 1200 degrees F. and slowly cooled. In the second case, it is heated to from 1500 to 1550 degrees F. and quenched, and then reheated to from 1300 to 1400 degrees F., and again quenched, and finally reheated to from 600 to 1200 degrees F. and slowly cooled. Nickel steel containing from 0.15 to 0.25 per cent of carbon may also be casehardened. The casehardening is carried out as follows: Carburize at a temperature of from 1650 to 1700 degrees F. and cool slowly in the carburizing mixture; then reheat to from 1450 to 1525 degrees F. and quench; reheat again to from 1300 to 1400 degrees F. and quench; and finally temper at a temperature of from 250 to 500 degrees F., according to the hardness of the case required on the casehardened material, and cool slowly.

The 0.15-per-cent carbon nickel steel, when casehardened, produces an exceedingly tough and strong core and a hard surface. It is used for casehardened gears and other casehardened parts which require both strength and hardness. The steels containing from 0.20 to 0.25 per cent of carbon are considered the best quality of nickel steels. That with 0.20 per cent of carbon is a good casehardening steel, and that with 0.25 per cent of carbon may also be successfully casehardened and has been found suitable for gears; it is used to a large extent for automobile transmissions. Nickel steel containing 0.30 per cent of carbon is used for shafts and axles requiring strength and toughness. In automobiles, for example, it is used for crankshafts, driving shafts, and transmission shafts. It is not suitable for casehardening, although it may be casehardened. Nickel steel with 0.35 per cent of carbon is used for the same purposes as the 0.30-per-cent carbon steel. The nickel steels with higher carbon content are not used to any large extent. By proper heat-treatment they may be made harder than the steels with lower carbon content, but the brittleness is increased.

Titanium Steels. — Titanium steel contains from 0.5 to 1 per cent of titanium. This steel is used for gears, locomotive tires, rails and castings, its special property being its ability to resist abrasion and frictional wear. Titanium steel bars may also be made that have exceptional resistance to torsional strains.

One example is cited where a bar 4 feet long and 1¼ inch square was twisted through seven complete revolutions without sign of fracture. In a structural steel having a tensile strength of 67,000 pounds per square inch and an elastic limit of 42,000 pounds per square inch, an addition of 0.5 per cent of titanium increased the tensile strength to 77,000 pounds per square inch, and the elastic limit to 51,700 pounds per square inch. The elongation and reduction of area was also slightly increased; at least, there was no decrease in these values. It is stated that titanium steel rails will wear only one-fifth as much as ordinary Bessemer rails under the same conditions in an equal period of time.

When titanium is used in cast iron, 0.5 per cent of titanium is said to increase the crushing strength of gray iron by 50 per cent. It has also been added with success in the crucible process to tool steels, giving the cutting tools much greater ductility and qualities somewhat resembling those of high-speed steel. In steel castings it is also easier to obtain a high tensile strength and elastic limit when introducing titanium.

Vanadium Steel. — Vanadium is used in steel either alone or in combination with chromium. Vanadium steels in which vanadium is used alone usually contain from 0.15 to 0.25 per cent of vanadium. The steel is valuable on account of its shock-resisting ability and is frequently used where exposed to repeated stresses. Vanadium increases the tensile strength and the elastic limit, and steel containing vanadium is used for springs, gears subjected to severe service, car axles, hammer piston rods, aeroplane parts, etc. As a rule, however, vanadium steel also contains chromium which is exceptionally valuable, as it combines a high elastic limit with great hardness. Vanadium is also used largely in tool steels both for cutting tools and for dies for forging machines.

Chrome-vanadium Steel. — Chrome-vanadium steel combines the properties obtained by adding chromium and vanadium separately to steel. The chromium increases the hardness and the elastic limit and the vanadium the shock-resisting capacity; hence, the resulting steel is one in which the properties of hard-

ness and strength are combined with ability to resist shocks and repeated stresses. Chrome-vanadium steel should contain about 0.90 per cent of chromium and 0.18 per cent of vanadium; the vanadium content should never be less than 0.12 per cent. Different properties are given to this steel by varying the amount of carbon. Commonly used steels have carbon contents varying from 0.15 to 0.50 per cent of carbon. Neither the sulphur nor the phosphorus content should exceed 0.04 per cent. The manganese content should be about 0.65 per cent. The chrome-vanadium steels that contain from 0.15 to 0.20 per cent of carbon are used mainly for casehardened parts. The 0.25-per-cent carbon steel may be casehardened, but is not suitable for this purpose. This steel, as well as those having a higher percentage of carbon, are used for a number of purposes where in the past plain carbon and nickel steels were used; they are heat-treated, but not casehardened. Chrome-vanadium steel containing as much as 0.40 per cent of carbon is used when a high degree of strength is required in combination with a moderate degree of toughness, as, for example, for high-duty shafts. The 0.45- and 0.50-per-cent carbon chrome-vanadium steels are suitable for gears and springs.

The heat-treatment to which chrome-vanadium steels are subjected vary according to the percentage of carbon present. The 0.15-per-cent carbon steel, when casehardened, is treated as follows: Carburize at a temperature of from 1650 to 1700 degrees F. and cool slowly in the carburizing mixture; then reheat to from 1600 to 1700 degrees F. and quench; and reheat again to from 1475 to 1550 degrees F. and quench. Then heat for tempering to from 250 to 550 degrees F. and cool slowly.

When heat-treated for strength only, the same steel should be treated as follows: Heat to from 1600 to 1700 degrees F. and quench in oil, and then reheat to some temperature between 500 and 1300 degrees F. and cool slowly. All chrome-vanadium steels with a carbon content of 0.40 per cent and less are treated in the same manner.

When heat-treated for strength, the 0.45- and 0.50-per-cent carbon chrome-vanadium steels are held for about one-half hour

at a temperature of from 1525 to 1600 degrees F. and permitted to cool slowly, after which they are reheated to from 1650 to 1700 degrees F. and quenched in oil, and again reheated for tempering to from 350 to 550 degrees F. and permitted to cool slowly.

In the annealed state, chrome-vanadium steels have practically the same strength as nickel steels with the same carbon content. When heat-treated, the 0.15-per-cent carbon steel has an elastic limit of from 50,000 to 90,000 pounds per square inch; the 0.30-per-cent carbon steel has an elastic limit of from 60,000 to 150,000 pounds per square inch; the 0.40-per-cent carbon steel has an elastic limit of from 65,000 to 175,000 pounds per square inch. The 0.45-per-cent carbon chrome-vanadium steel, when heat-treated, has an elastic limit of from 150,000 to 200,000 pounds per square inch; and the 0.50-per-cent carbon steel may reach an elastic limit of 225,000 pounds per square inch. The great strength of these steels, however, is obtained by a sacrifice of elongation, the elongation in the higher carbon steels being only from 2 to 10 per cent.

Chrome-vanadium steels are used when a better material than nickel steel is required. They are easily forged and are not as difficult to machine as chrome-nickel steels. They are preferably made in crucible or electric furnaces, although open-hearth chrome-vanadium steel is also used. The open-hearth steel, however, is not uniform, and for springs of the best quality there is nothing superior to a crucible chrome-vanadium steel.

Nickel-chromium Steel. — Nickel-chromium steels are used to a considerable extent in the automobile industries, and also for armor-plate steel. The steel has remarkable qualities with regard to strength, hardness, and ductility. The nickel-chromium steel as used in the industries is divided into three distinct classes — low, medium, and high nickel-chromium steels. In the low nickel-chromium steels, the percentage of nickel varies from 1.00 to 1.50 per cent, and that of chromium, from 0.30 to 0.75 per cent. In the medium nickel-chromium steels, the percentage of nickel is about 1.75 per cent, and that of chromium, about 1.00 per cent. In the high nickel-chromium steels,

the percentage of nickel is about 3.5 per cent, and that of chromium, 1.5 per cent. The carbon content in either of these steels may vary from 0.15 to 0.50 per cent, according to the uses for which the steels are intended. The manganese content should be about 0.65 per cent in the "low" steels, and 0.45 per cent in the "medium" and "high" steels, and the content of either phosphorus or sulphur must not exceed 0.04 per cent in any of the steels. The low nickel-chromium steels with carbon up to 0.20 per cent are mainly intended for casehardening, while those with from 0.25 to 0.40 per cent of carbon are used for general machine parts requiring strength and toughness. When the carbon content is as high as 0.45 or 0.50 per cent, the steel may be used for gears. Medium nickel-chromium steels are used for practically the same purposes as low nickel-chromium steels.

The high nickel-chromium steels are used for parts of important character, where unusual strength is required. The qualities with a low carbon content are used for casehardening purposes; those with a medium carbon content, for heat-treated parts generally; and those with from 0.45 to 0.50 per cent of carbon, for gears where extreme strength and hardness are required, the carbon content being sufficiently high to cause the material to harden, when quenched, without being casehardened. This steel is difficult to machine and forge. Before machining, it must be annealed, and when forged it must be kept at a high, almost plastic, heat, and should not be hammered nor worked at ordinary forging temperatures. At the same time, too high a temperature must be avoided in order not to injure the steel.

When low and medium nickel-chromium steels are casehardened, the following process should be adopted: Carburize at a temperature between 1650 and 1700 degrees F. and cool slowly in the carburizing material; then reheat to from 1450 to 1525 degrees F. and quench; and reheat again to from 1300 to 1400 degrees F. and quench. Finally temper at from 200 to 500 degrees F. and cool slowly. When high nickel-chromium steel is casehardened, practically the same procedure should be followed, except that the first reheating should be at a temperature of about 50 degrees less than that just specified.

The heat-treatment to which low and medium nickel-chromium steels should be subjected in order to increase the strength when they contain 0.40 per cent or less of carbon is as follows: Heat to from 1500 to 1550 degrees F. and quench, and then reheat to from 600 to 1200 degrees F. and cool slowly. A double reheating treatment may also be employed as follows: Heat to from 1500 to 1550 degrees F. and quench, reheat to from 1300 to 1400 degrees F. and quench, and finally reheat to from 600 to 1200 degrees F. and cool slowly. This latter treatment is also suitable for low and medium nickel-chromium steels containing from 0.45 to 0.50 per cent of carbon.

The high nickel-chromium steels containing from 0.20 to 0.35 per cent of carbon may be heat-treated in a similar manner to the low and medium nickel-chromium steels, except that the heating temperature should be in every case about 50 degrees F. less than for these steels. The 0.45-per-cent high nickel-chromium steel should be heat-treated as follows: Hold at a temperature of from 1475 to 1525 degrees F. for half an hour and then cool slowly; reheat to from 1450 to 1500 degrees F. and quench in oil; and finally reheat for tempering to from 250 to 550 degrees F. and cool slowly.

Natural Alloy Steel. — Natural alloy steel is a nickel-chromium steel deriving its name from the fact that the steel is not obtained by adding nickel and chromium to steel, but is manufactured from an ore in which nickel and chromium are alloyed with iron by nature. These natural alloy steels contain from 1.0 to 1.5 per cent of nickel, from 0.2 to 0.7 per cent of chromium, from 0.15 to 1.5 per cent of carbon, and from 0.5 to 0.8 per cent of manganese. These steels are made by the open-hearth process and are largely used in the manufacture of automobile parts. Those being low in carbon are suitable for casehardening and also for cold-drawing, for seamless tubes, drop-forgings, etc. The grades having high percentages of carbon are suitable for axles, transmission gears, etc.

Copper Alloy Steel. — A steel containing from 0.30 to 0.35 per cent of carbon, from 1.50 to 1.80 per cent of nickel, and from 0.50 to 0.80 per cent of copper has been found equal in its proper-

ties to a 3-per-cent nickel steel, and is a suitable substitute for this steel, the composition of which would make it more expensive. If 0.50 per cent of chromium is added to the alloy mentioned, the properties of the steel will equal those of nickel-chromium steel having 1 per cent of chromium and 3 per cent of nickel; hence, the influence of a small percentage of copper is very marked. It is claimed that this alloy steel, without chromium, may be expected after heat-treatment to have an elastic limit of 65,000 pounds per square inch, and with 0.50 per cent of chromium, to have an elastic limit of 110,000 pounds per square inch with an elongation of 17 per cent and a reduction of area of 44 per cent. It is possible that in the future this steel will be more generally used, if it is found that the claims made for it are backed up by practical experience.

CHAPTER XII

HIGH-SPEED STEEL

IN the manufacture of steel, there are two distinct branches of work which have been referred to in preceding chapters. One is the production of steel suitable for use in the construction of machinery, buildings, bridges, and an endless variety of other things which are essential to modern industrial life. The second branch of the steel industry is in producing steels which may be used in making the tools required for cutting and otherwise forming the various parts that enter into the different kinds of machines and structures. The steels which (when properly heat-treated) are capable of cutting other steels or parts made of either wrought iron or cast iron constitute a very important class, and this chapter deals with some of the wonderful developments which have been made in the manufacture of such steels. When ordinary tool or carbon steel is used for cutting metals such as cast iron or steel, if the speed or rate at which the cutting is done exceeds a certain amount, the excessive heat generated by the friction at the cutting end of the tool causes the steel to lose, to some extent at least, the hardness obtained as a result of heat-treatment; consequently, the cutting edge is worn away and the tool no longer cuts effectively.

The discovery of a steel which is commonly known, at the present time, as "high-speed steel," marked a new epoch in the machine building field. High-speed steel, as its name implies, is capable of cutting metal at much higher speeds than ordinary carbon steel. The result is that metal can be removed much more rapidly in connection with machining operations such as turning, planing, milling, drilling, etc. When using plain carbon steel, the temperature of the cutting end must be kept below 500 or 550 degrees F., but high-speed steels retain sufficient hardness for cutting metals even when the end is heated to a

dull red or to 1100 or 1200 degrees F. Because of this fact, such steel is said to possess the property of *red hardness*.

High-speed steel has proved to be so much superior to carbon steel, especially for rapid metal-cutting operations, that it has revolutionized machine shop practice. The introduction of this steel also made it necessary to re-design machine tools generally, so that they could withstand the greatly increased stresses imposed upon them as a result of high-duty operation made possible by the improved cutting tools. Some of the more important facts relating to the discovery of the "self-hardening steel" which preceded what is now known as high-speed steel will be referred to and then the influence of different elements and the general characteristics of steels of this class will be referred to.

Origin of Self-hardening Steel. — The origin of modern high-speed steels may be traced back to a wonderful discovery made by Robert F. Mushet in 1868. Experiments were being made with the use of manganese in the production of Bessemer steel, and at first there was no idea of improving tool steel. During these experiments it was discovered that one of the bars of steel had the property of hardening after being heated, without quenching or cooling it rapidly in the manner required to harden carbon steel. This steel, which was afterwards known as mushet or self-hardening steel, was found to contain tungsten. The newly discovered steel which possessed the property of hardening when allowed to cool slowly without quenching, proved to be harder than steel which was quenched in the usual way. This discovery of self-hardening or air-hardening steel, as it was also called, led to numerous experiments with different elements in various combinations and, as a result, an alloy steel was obtained which was superior to carbon steel for rapid machining operations. The discovery was made later that the quality of the steel could be improved if the cutting end were reheated and cooled in an air blast, instead of being allowed to cool by simply exposing the heated steel to the atmosphere. An analysis of a typical mushet self-hardening steel showed the following composition: Tungsten, 5.441 per cent; chromium, 0.398 per cent;

at a temperature of from 1525 to 1600 degrees F. and permitted to cool slowly, after which they are reheated to from 1650 to 1700 degrees F. and quenched in oil, and again reheated for tempering to from 350 to 550 degrees F. and permitted to cool slowly.

In the annealed state, chrome-vanadium steels have practically the same strength as nickel steels with the same carbon content. When heat-treated, the 0.15-per-cent carbon steel has an elastic limit of from 50,000 to 90,000 pounds per square inch; the 0.30-per-cent carbon steel has an elastic limit of from 60,000 to 150,000 pounds per square inch; the 0.40-per-cent carbon steel has an elastic limit of from 65,000 to 175,000 pounds per square inch. The 0.45-per-cent carbon chrome-vanadium steel, when heat-treated, has an elastic limit of from 150,000 to 200,000 pounds per square inch; and the 0.50-per-cent carbon steel may reach an elastic limit of 225,000 pounds per square inch. The great strength of these steels, however, is obtained by a sacrifice of elongation, the elongation in the higher carbon steels being only from 2 to 10 per cent.

Chrome-vanadium steels are used when a better material than nickel steel is required. They are easily forged and are not as difficult to machine as chrome-nickel steels. They are preferably made in crucible or electric furnaces, although open-hearth chrome-vanadium steel is also used. The open-hearth steel, however, is not uniform, and for springs of the best quality there is nothing superior to a crucible chrome-vanadium steel.

Nickel-chromium Steel. — Nickel-chromium steels are used to a considerable extent in the automobile industries, and also for armor-plate steel. The steel has remarkable qualities with regard to strength, hardness, and ductility. The nickel-chromium steel as used in the industries is divided into three distinct classes — low, medium, and high nickel-chromium steels. In the low nickel-chromium steels, the percentage of nickel varies from 1.00 to 1.50 per cent, and that of chromium, from 0.30 to 0.75 per cent. In the medium nickel-chromium steels, the percentage of nickel is about 1.75 per cent, and that of chromium, about 1.00 per cent. In the high nickel-chromium steels,

the percentage of nickel is about 3.5 per cent, and that of chromium, 1.5 per cent. The carbon content in either of these steels may vary from 0.15 to 0.50 per cent, according to the uses for which the steels are intended. The manganese content should be about 0.65 per cent in the "low" steels, and 0.45 per cent in the "medium" and "high" steels, and the content of either phosphorus or sulphur must not exceed 0.04 per cent in any of the steels. The low nickel-chromium steels with carbon up to 0.20 per cent are mainly intended for casehardening, while those with from 0.25 to 0.40 per cent of carbon are used for general machine parts requiring strength and toughness. When the carbon content is as high as 0.45 or 0.50 per cent, the steel may be used for gears. Medium nickel-chromium steels are used for practically the same purposes as low nickel-chromium steels.

The high nickel-chromium steels are used for parts of important character, where unusual strength is required. The qualities with a low carbon content are used for casehardening purposes; those with a medium carbon content, for heat-treated parts generally; and those with from 0.45 to 0.50 per cent of carbon, for gears where extreme strength and hardness are required, the carbon content being sufficiently high to cause the material to harden, when quenched, without being casehardened. This steel is difficult to machine and forge. Before machining, it must be annealed, and when forged it must be kept at a high, almost plastic, heat, and should not be hammered nor worked at ordinary forging temperatures. At the same time, too high a temperature must be avoided in order not to injure the steel.

When low and medium nickel-chromium steels are casehardened, the following process should be adopted: Carburize at a temperature between 1650 and 1700 degrees F. and cool slowly in the carburizing material; then reheat to from 1450 to 1525 degrees F. and quench; and reheat again to from 1300 to 1400 degrees F. and quench. Finally temper at from 200 to 500 degrees F. and cool slowly. When high nickel-chromium steel is casehardened, practically the same procedure should be followed, except that the first reheating should be at a temperature of about 50 degrees less than that just specified.

the time mentioned without using a specially designed furnace. After heating the tool as described, it should be cooled rapidly down to or below 1550 degrees F., and then it may be cooled either rapidly or slowly from this point down to the temperature of the atmosphere. The preferable method of cooling from the high heat down to 1550 degrees F. is by plunging the tool into a bath of red-hot molten lead which is below a temperature of 1550 degrees F. It is very important to avoid any increase of temperature during the cooling period, as any temporary rise of temperature will injure the tool unless this increase occurs at temperatures below 1240 degrees F. After a tool has received the "high heat-treatment," it is subjected to a second or "low heat-treatment" which consists of reheating to a temperature somewhere between 700 and 1240 degrees F. A lead bath is preferable for this second heat-treatment which should be for a period of about five minutes. A temperature of about 1150 degrees F. is liable to give the best results. The tool may be cooled either rapidly or slowly to the temperature of the air.

When high-speed steel tools must be heated in an ordinary forge, a deep bed either of coke or of first-class soft coal is recommended. Several tools should be laid with their ends at a slight distance from the hottest part of the fire, so that they are being heated while the temperature of the fire is increasing to the proper degree. Then the tools are heated one at a time over the hottest section of the fire and as rapidly as possible up to a temperature just below the melting point. In order to secure a more uniform heating, the tool should be repeatedly turned over. As soon as each tool receives its high heat, the cutting end is placed under a heavy air blast and is allowed to cool to the temperature of the atmosphere before being removed.

Production of High-speed Steel. — High-speed steel may be produced either by means of the crucible process or in the electric furnace. The methods of making carbon and high-speed steel by the crucible process are practically the same so far as equipment and general procedure is concerned. The principal difference is in the materials which are placed in the crucible and which control the composition of the steel. The different

materials required, such as tungsten, charcoal for supplying the carbon, chromium, or whatever elements are to be combined with the iron, are proportioned and measured very carefully, so that the composition of the steel will conform to the formula which has been adopted. These different elements should preferably be placed in the bottom of the crucible and beneath the small pieces of iron.

The ores from which tungsten, molybdenum, chromium, etc., are obtained are reduced in the electric furnace and either to the metallic state or to a ferro-alloy. Ferrotungsten, which is an
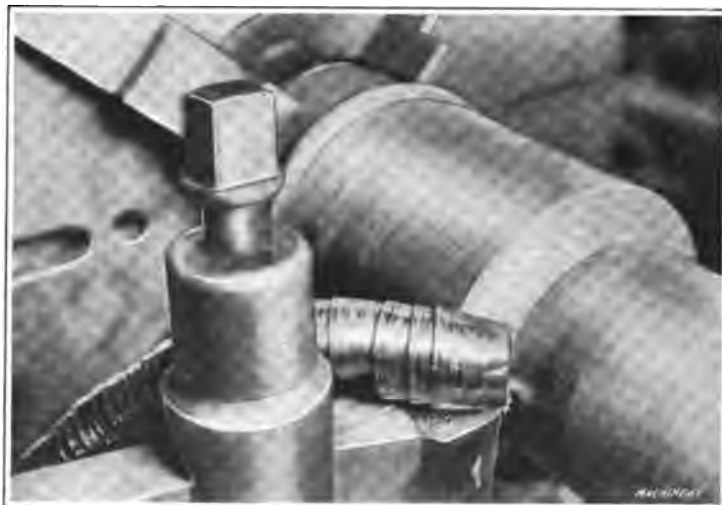
Fig. 1. High-speed Steel Turning Tool at Work

alloy of iron and tungsten, contains from 50 to 85 per cent of tungsten. It may be produced directly from tungsten-bearing ores more easily than metallic tungsten, and it is claimed that less tungsten is lost when introduced into the steel as ferrotungsten. Pure iron free from phosphorus, sulphur, and other impurities is very essential. Some steel-makers consider it necessary to use Swedish or Dannemora iron for producing the best grades of high-speed steel, because of the small percentage of impurities found in these irons. Other steel-makers contend that native muck-bar iron meets all the requirements. In the pro-

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duction of a first-class high-speed steel, careful tests and inspection are necessary during the process of manufacture to make sure that the steel conforms to the required composition and to guard against defects or flaws.

Effect of Different Elements in High-speed Steels. — The effect of different elements entering into the composition of high-speed steels and the reasons why tungsten, chromium, and other elements give steels of this class such unusual properties will be more apparent by considering first the changes that occur in the hardening of ordinary carbon steel. As explained in Chapter V in connection with the microscopic study of heat-treated steels, the pearlite, ferrite, and cementite of annealed steels are replaced by other constituents when the steel is subjected to the heat-treatment required for hardening and tempering. Annealed steel containing approximately 0.90 per cent of carbon is composed entirely of pearlite. Incidentally, the composition of most of the steels of which cutting tools are made is largely pearlite before the steel is hardened. Steels that contain less than 0.90 per cent of carbon have, in addition to pearlite, ferrite, which increases as the carbon content decreases. On the other hand, if there is more than 0.90 per cent of carbon, the steel is composed of pearlite and cementite. Now if any of these steels are heated sufficiently, the elements referred to change to austenite. If the annealed steel has 0.90 per cent of carbon and is all pearlite, the change to austenite occurs at about 1355 degrees F., but the effect of either ferrite or cementite is to increase the temperature at which conversion to austenite occurs. After a steel has been heated sufficiently to change it to the austenitic condition, some of this austenite may remain after the steel has been cooled to the temperature of the atmosphere, although this necessitates very rapid cooling. Were it not for the carbon element, the austenite could not be retained even though the rate of cooling were extremely rapid, the effect of carbon being to obstruct the change and assist in keeping the steel in the austenitic condition. The carbon, therefore, acts as a fixing agent, and if there is a carbon content of over 1 per cent, the austenite may be fixed in cold steel, provided the steel is heated to a white

heat and is then cooled very rapidly by using a quenching bath such as iced brine, which is below the freezing point of water.

The ordinary methods of heat-treatment produce martensite which is harder than austenite. Martensite is formed between the change from austenite to pearlite, the order being from austenite to martensite, as the steel cools. The change from austenite to martensite is difficult to prevent, because it occurs rapidly, the change from martensite to pearlite being relatively slow. While the hardness of martensite is a desirable quality, steel in this condition is too brittle for most purposes, and it is necessary to sacrifice the hardness by tempering, which toughens the steel and makes it better able to withstand shocks. The practical effect of tempering is to reduce the martensite or "let it down" toward the pearlite condition. The formation of troostite (which occurs between martensite and pearlite) and of sorbite as the result of tempering was explained in Chapter V.

Influence of Carbon on High-speed Steels. — Among the elements found in high-speed steels are carbon, tungsten, molybdenum, chromium, vanadium, manganese, uranium, and silicon. These various elements are, of course, used in a great variety of combinations and proportions, and in many cases the exact composition is kept secret by the steel-maker. The carbon content may vary from 0.4 to 2 per cent or more. At one time, most high-speed steels had a carbon content varying between 1 and 2 per cent, although later many steel-makers reduced this amount and high-speed steels having less than 1 per cent of carbon are now common. Experiments have indicated that when a high-speed steel is hardened by the method previously referred to, of heating almost to the melting point and then rapidly cooling in a strong air blast, a carbon content varying from 0.4 to 0.9 per cent gives the best results. When there is more carbon, considerable difficulty is experienced in forging the steel, and its cutting efficiency is also less. The steel is, in addition, more brittle and tends to break, particularly if there is unequal or intermittent cutting. The effect of carbon in high-speed steel is to increase the time required for the change from the austenitic to the pearlitic condition.

Influence of Manganese. — Manganese, like carbon, delays the change from austenite to pearlite, but it acts in a different way. The effect of carbon is to obstruct the change, whereas manganese causes it to occur at a lower temperature, and as the manganese content increases, the temperature at which the change takes place decreases. The result is that, when there is about 12 per cent of manganese, the change to the pearlitic condition does not occur even when the steel is cold; consequently, such a steel is self-hardening and even though it is annealed, austenite and ordinarily martensite remain fixed. The change from austenite to martensite occurs rapidly and, for this reason, is difficult to prevent. Manganese steel which cools slowly will be more or less martensitic, whereas, if it is cooled rapidly from a white heat, the austenitic condition will be obtained. Such steel will not be as hard as that which is martensitic, but it will not be brittle like the latter. In fact, steel in the austenitic condition is tough, but the elastic limit is low. Manganese steel is not suitable for cutting tools, because the edge of the tool will not withstand the severe service to which metal-cutting tools are subjected.

Influence of Tungsten. — Tungsten is a very important element in high-speed steels and is utilized very extensively in the manufacture of steels of this class. Tungsten is another element which delays the change from austenite to pearlite. The effect is so pronounced that the change will be prevented entirely if there is 7 per cent or more of tungsten, even though the heated steel is allowed to cool slowly in the air. For this reason, it is necessary to cool a tungsten steel at an extremely slow rate in order to anneal it or to change it to the pearlite condition. The reason why high-speed steels in general can be heated considerably as the result of high cutting speeds and excessive friction is that some element (or combination of elements), such, for example, as tungsten, so changes the characteristics of the steel that the increase of temperature does not reduce it to the pearlitic stage, the same as with ordinary carbon steel. The martensite in carbon steel will not remain fixed if the steel is heated beyond a certain point, but if there is sufficient tungsten in the com-

position, the martensite remains even though the temperature is raised above that required for tempering. The natural tendency is for the martensite to change to troostite and finally back

Fig. 2. Planing with a High-speed Steel Tool

to pearlite, or to the condition normal to annealed steel. The effect of tungsten to resist change from the martensitic condition explains why steel may have the property of red hardness.

Experiments made with a tungsten content varying from 9 to 27 per cent showed that from 9 to 16 per cent the steel becomes

very brittle, but the cutting efficiency greatly increases. No better results, however, were obtained by increasing the tungsten content to more than 16 per cent. When the amount of tungsten varied between 18 and 27 per cent, the steel lost its brittleness and became softer and tougher. While this latter steel did not stand up so well, it did have the property of cutting very "cleanly." The composition of tungsten steel specified for the Navy Department is as follows (when two figures are given these represent minimum and maximum percentages): Tungsten, from 16 to 20 per cent; carbon, from 0.55 to 0.75 per cent; chromium, from 2.50 to 5 per cent; manganese, from 0.05 to 0.30 per cent; phosphorus, 0.015 per cent; silicon, 0.30 per cent; sulphur, 0.02 per cent; vanadium, from 0.35 to 1.5 per cent. Iron is the element which represents the remaining percentage in the composition of the steel.

Influence of Chromium. — The effect of chromium is similar to carbon in that it obstructs the natural tendency of heated steel to change from the austenitic to the pearlitic condition. Experiments which showed that the best carbon content varied from 0.4 to 0.9 per cent were followed by other tests to determine the effect of chromium varying from 1 to 6 per cent. A low percentage of chromium was found to produce a tough steel which was very satisfactory for cutting cast iron or comparatively soft steels, but this steel was not very effective when applied to harder materials. For the latter class of work, steel having a larger amount of chromium was found to be preferable, because the increase of chromium produces a harder steel. In order to obtain the best results, however, it is necessary to decrease the carbon in the steel as the chromium content is increased. Chromium and carbon will not produce a self-hardening steel, although if there is approximately 1 per cent of carbon and 1 or 2 per cent of chromium, such steel becomes very hard when cooled rapidly, and the hardness resulting from the chromium causes the steel to be less brittle than plain carbon steel. If toughness is the desirable quality, there should be about 1.5 per cent of chromium, whereas, if an extremely hard steel is desired, the chromium content may be increased to from 4 to 6 per cent.

While a chromium-carbon steel is not self-hardening, chromium combined with manganese produces a steel which has the self-hardening property. The manganese content in this case is only a few per cent and very much less than is found in manganese steel.

Influence of Vanadium. — Many of the high-speed steels now manufactured contain from 0.75 to 1 per cent of vanadium, although when this element was first used the content ordinarily varied from about 0.2 to 0.3 per cent. An increase in the amount of vanadium, however, was found to give better results. Tests made to determine the influence of vanadium on the durability of steel at different cutting speeds showed that a tool steel containing 0.3 per cent of vanadium may have a 10 per cent higher cutting speed than a steel without vanadium. By increasing the vanadium content to 0.6 per cent, the cutting speed was increased 20 per cent, and with 0.9 per cent of vanadium, an increase of 30 per cent in the cutting speed was practicable. Another series of tests in which the same cutting speed was maintained showed that the time between grindings was doubled in the case of an 0.3-per-cent vanadium steel, quadrupled with an 0.6-per-cent vanadium steel, and 0.9 per cent increased the period between grindings eight times.

Influence of Molybdenum. — The effect of molybdenum on steel is similar to that of tungsten. One of the noteworthy properties of molybdenum steels is that they do not require such a high temperature for hardening as is necessary in the case of tungsten steels. The latter are commonly heated to 2200 or 2300 degrees F., whereas a molybdenum steel is injuriously affected if heated much above 1800 degrees F. The cutting efficiency of a high tungsten steel is increased somewhat by the addition of from 0.5 to 3 per cent of molybdenum, although the advantage is not in proportion to the increase in cost.

Influence of Silicon. — High-speed steels may contain silicon varying from a mere trace up to 4 per cent. The addition of silicon up to about 3 per cent is supposed to increase the cutting efficiency, particularly if the tools are applied to hard material; but higher silicon contents have the opposite effect and reduce

the efficiency. A high silicon content increases the hardness of the steel, but also makes it brittle.

Tungstenless High-speed Steel. — A high-speed steel containing no tungsten whatever has been produced by a Sheffield concern and is claimed to be equal in durability and hardness to any high-speed steel containing tungsten. This comparatively new steel (which is called "cobaltcrom") is said to be suitable for making milling cutters, twist drills, reamers, taps, forming tools, and screw-cutting and finishing tools in general. It is further claimed that the endurance of the steel is not only equal to any tungsten high-speed steel, but that it is tougher, produces a better finish, and does not crack in hardening, even in the case of tools of intricate shape. This steel is hardened at a temperature of about 1830 degrees F., as compared with the higher temperatures of 2300 or 2400 degrees F. for tungsten high-speed steel. The specific gravity of cobaltcrom is about 10 per cent less than that of tungsten high-speed steel. It contains about 1.5 per cent of carbon, 12.5 per cent of chromium, and 3.5 per cent of cobalt.

Uranium High-speed Steel. — It is claimed that uranium possesses powerful deoxidizing and de-nitrogenizing effects when applied to high-speed steel, and that it increases the toughness and durability of the steel. The Standard Alloys Co., Pittsburg, Pa., recommends that this steel be heated to between 2200 and 2300 degrees F., and if it is to be "drawn back," the temperature should be about 900 degrees F. This steel can be cooled in an air blast or quenched in oil, but the former method appears preferable. The claim made for uranium high-speed steel is that it has to a marked degree the property of toughness and is capable of severe duty without any breaking away or crumbling along the cutting edge of a properly ground tool.

Semi-high-speed Steel. — A semi-high-speed steel may be defined as a steel which is not capable of withstanding such fast cutting speeds as a steel ordinarily designated as high-speed; the semi-high-speed steel, however, is superior in the matter of cutting speed to ordinary carbon steel. Owing to the cost of high-speed steels, the semi-high-speed steel was produced to

meet the demand for a cheaper steel which could be used just as well for certain purposes. For instance, extremely high speeds and heavy cuts are necessarily impracticable for some operations, as in the case of certain wood-working operations where a cutter having greater durability than one made of the best carbon steel would last almost indefinitely and there is no good reason for using the more expensive high-speed steel. These "intermediate" or semi-high-speed steels are practically the mushet or self-hardening steels, although some appear to be manganese rather than tungsten steels. Steel made according to the following composition is a typical example of the semi-high-speed class: Carbon, 1.190 per cent; tungsten, 7.560 per cent; chromium, 3.340 per cent; manganese, 0.460 per cent; phosphorus, 0.024 per cent; sulphur, 0.025 per cent; silicon, 0.200 per cent.

The composition of another semi-high-speed steel which corresponds more closely to mushet steel is as follows: Carbon, 0.94 per cent; tungsten, 4.78 per cent; chromium, 0.69 per cent; manganese, 0.27 per cent; phosphorus, 0.01 per cent; sulphur, 0.01 per cent; silicon, 0.11 per cent. The first steel referred to is somewhat higher in tungsten than mushet steel, and the second is lower in chromium; both steels also contain less carbon than was found in most mushet steels. A steel which is classified as intermediate steel and has proved very satisfactory for cutting wood and metals of moderate hardness and also for making blanking and stamping dies has the following composition: Carbon, 1.03 per cent; tungsten, 0.46 per cent; manganese, 0.30 per cent; phosphorus, 0.025 per cent; sulphur 0.009 per cent; silicon, 0.008 per cent. This is a dense steel which requires very slow and careful heating to a temperature of about from 1500 to 1550 degrees F. for cutting tools and a somewhat lower temperature for tools that must withstand pressure or blows. This steel must be hardened by quenching and the temper should be drawn the same as with carbon tool steels. It is claimed that this steel is much tougher than carbon tool steel, although it does not differ from the latter greatly. A steel which is designated as a "finishing steel" and has given excellent results for this kind of work contains 1.25 per cent of

carbon; 2.25 per cent of tungsten; 0.28 per cent of chromium; 0.85 per cent of manganese; and 0.21 per cent of silicon. There are various other steels in the intermediate or semi-high-speed steel class which have a tungsten content or a molybdenum equivalent less than that found in high-speed steels.

General Hardening Practice for High-speed Steel. — The exact heat-treatment recommended for different kinds of high-speed steel varies more or less, and it is advisable to follow the directions given by the steel-makers. The general practice conforms quite closely to that previously referred to in connection with the Taylor and White experiments; that is, the cutting end is heated slowly to a temperature of from 1500 to 1800 degrees F. and then rapidly up to 2200 or 2300 degrees F., or until the end is at a dazzling white heat and shows signs of melting. The tool point is often cooled by plunging it into a bath of oil such as linseed or cottonseed or by inserting it in a strong blast of dry air. Taylor's conclusion in regard to this point, as recorded in his treatise "On the Art of Cutting Metals," is that cooling the tool in an air blast from the high heat will produce as good and uniform a tool as by any other method, outside that of plunging it into the hot lead bath, as previously described. It was claimed that the more rapid methods of cooling either by plunging into water or oil rendered the tool more liable to fire cracks and made the body more brittle and liable to break in service, particularly if there was any lack of uniformity in the heating. It was claimed further that cooling in water or oil gives no greater degree of red hardness than can be obtained by cooling in an air blast, regardless of the chemical composition of the steel.

When oil baths are used for quenching, the temperature varies from that of the room up to 350 degrees F., depending upon the steel used. These oil baths are now used extensively in preference to the air blast formerly recommended by most steel-makers. It is important to quench the heated steel very quickly after removing it from the fire or furnace. In addition to linseed or cottonseed oil for quenching baths, thin lard oil and also kerosene oil are sometimes used. If a cutting tool requires ex-

tremely hard cutting edges, the latter are heated to the fusing point and then the tool is quenched rapidly in thin lard oil; kerosene oil may also be used if extreme hardness is desired. If kerosene is used, a galvanized iron tank having close fitting covers is desirable to avoid trouble from flames. The hardening methods previously referred to apply to tools which may be ground after hardening. When it is not practicable to grind the cutting edge after hardening, any melting or fusing of the cutting edges must, of course, be prevented. The hardening of such tools will be considered later.

Tempering High-speed Steel. — High-speed steel, like carbon steel, is often tempered after hardening to reduce the brittleness and to increase the toughness by sacrificing hardness. Large heavy tools made of high-speed steel (such as are used on lathes and planers) ordinarily are not tempered, because the cutting edges are well supported. The tools, however, that are relatively weak are frequently tempered to suit the class of work for which they are intended. The steel to be tempered may be heated in an oven furnace or in a bath of oil or lead. Another approved method is to cover the steel with clean dry sand contained in a metal pan which is heated by a gas or oil burner, or in any convenient way. A pyrometer should be used to indicate the temperature. A general idea of the variations in temperatures for tempering different classes of tools may be obtained from the following data: For tempering milling cutters, 400 degrees F.; for drills and reamers, 440 degrees F., if the tools are large, or 460 degrees F. in the case of small sizes; taps and dies for thread cutting, 490 degrees F.

Annealing High-speed Steel. — The annealing of high-speed steel is desirable partly because it removes the internal strains that may have arisen, due to hammering and rolling. Annealing also renders the steel sufficiently soft to be machined into any desired form for making milling cutters, drills, etc. An additional advantage is that it minimizes risks of cracking when the steel has to be reheated for hardening. In cases of intricately shaped tools having sharp-cornered recesses, fine edges, or delicate projections, which are liable to unequal expansion and

contraction, annealing tends to reduce cracking to a minimum.
Increased ductility is also imparted by annealing; this is espe-
cially necessary in tools subjected to sudden shocks due to
intermittent cutting, such as in planing and slotting or when
suddenly meeting projections or irregularities on the work
operated upon.

The annealing of high-speed steel should be done preferably
in muffle furnaces designed for heating by radiation only, a
temperature of 1500 degrees F. being maintained for from twelve
to eighteen hours, according to the size and shape of the bars.
A series of experiments made to determine the proper temperature
to which to heat high-speed steel for annealing gave the following
results: When the steel was heated to below 1250 degrees F.
and slowly cooled, it retained the original hardness and brittle-
ness imparted to the steel in forging. When heated to between
1250 and 1450 degrees F., the Brinell test indicated that the
steel was soft, but impact tests proved that the steel still retained
its original brittleness; however, when heated to between 1475
and 1525 degrees F., the steel became very soft, it had a fine-
grained fracture, and all of the initial brittleness had entirely
disappeared. By carrying these tests to 1600, 1750, and 1850
degrees F., it was found that the steel became very soft, but there
was a gradual increase in brittleness and in the size of the grain,
until at 1850 degrees F. the steel became again as brittle as unan-
nealed steel; the fracture at this temperature was dull and
showed marked decarburization.

Dried air-slaked lime was used as a packing medium in making
these tests, and the steel was packed in tubes sealed air-tight
on both ends. The decarburization that took place was probably
due to the oxygen in the air that had filled the intervening spaces
between the particles of lime. This decarburization would not
have taken place if powdered charcoal had been used; the latter
would have supplied all the carbon necessary to combine with
any oxygen present in the tubes.

Annealing Methods. — A method recommended by one of the
largest American high-speed tool steel manufacturers is to use
an iron box or pipe of sufficient size to allow at least one-half

inch of packing between the pieces of steel to be annealed and the sides of the box or pipe. (It is not necessary that each piece of steel to be annealed be kept separate from every other piece, but only that the steel be prevented from touching the sides of the annealing pipe or box.) This pipe is packed carefully with powdered charcoal, fine dry lime, or mica, and is covered with a cap, which should be air-tight; if it is not, it should be luted on with fireclay. The pipe is then heated slowly to a full red heat, about 1475 or 1500 degrees F., and held at this heat for from two to eight hours, depending upon the size of the pieces to be annealed. (A piece measuring 2 by 1 by 8 inches requires about three hours' time.) It is then cooled as slowly as possible, care being taken not to expose it to the air until cold; a good way is to allow the box or pipe to remain in the furnace until cold.

The method used by another manufacturer has the objection that the pieces annealed will scale off somewhat, but as the surface is generally machined away, this objection is of no importance for many classes of work. The method is as follows: Pack the tools directly in the oven, one on top of the other, entirely filling the furnace if necessary. Heat the furnace to a temperature not exceeding 1700 or 1750 degrees F., which should not require more than three hours, and maintain this heat for about two hours, or until the temperature of all the tools has been raised to that of the furnace itself. (When smaller pieces are to be annealed, it is sufficient to maintain the heat for about one hour.) Shut off the heat and at the same time close all holes, such as burner and draft holes, as carefully as possible and let the tools cool off in the furnace. This cooling takes place much more quickly than when the other method is employed, because the tools are not packed; hence, there is a saving in time not only in the heating but also in the cooling. The greater part of the expense of annealing is thus saved on account of the saving in fuel, and the elimination of the packing, packing materials, and the boxes.

When it is desired to anneal only a few small pieces, high-speed steel can be "water annealed" by a method similar to that used for carbon steel. The temperature to which the steel

is raised, however, is not as high as for carbon steel. In water annealing, the piece to be annealed is gradually and uniformly heated to 760 degrees F. It is then taken from the furnace and plunged into a bath of pure water, previously heated to a temperature of 150 degrees F., where it is permitted to cool until reduced to the temperature of the bath. This steel can be drilled, filed, or machined into any form with little difficulty. The more care devoted to the heating, the better will be the results. To heat rapidly will induce internal strains and greatly increase the risk of breakage when the pieces are plunged into the water bath.

Heat-treatment of Tools having Fine Edges. — When high-speed steel is used for making tools having fine cutting edges, and especially when such edges either cannot be ground or can only be partially ground after hardening, the hardening operation is more difficult than in the case of forged tools for the lathe, planer, etc., because the high hardening temperature required is liable to injure the cutting edges. For instance, it is rather difficult to harden such tools as taps, threading dies, gear-cutters, or other form milling cutters, twist drills, reamers, etc., because any melting or fusing of the cutting edges would be objectionable and might spoil the tool, whereas, in the case of forged turning and planing tools, the fused end is readily reshaped by grinding. Tools which cannot be fused without injuring them have been heated in barium-chloride baths so that the steel could not be heated to a higher temperature than that of the bath itself, which is very close to the melting point   Barium chloride, however, has an injurious or deteriorating effect upon the surface of the steel, and it is considered objectionable by many manufacturers.

One method of hardening tools of the kind referred to requires the use of a special muffle furnace which may be heated either by gas or oil. This furnace has two chambers lined with fire-clay and a series of burners at the rear. The furnace should be under such control that a temperature of 2200 degrees F. may be maintained in the lower chamber while the upper one is at a much lower temperature. Holes extending through cutters or

other tools should preferably be filled with fireclay before inserting them in the furnace. These tools are first placed on top of the furnace until warm; they are then inserted in the upper chamber for heating to about 1500 degrees F. or to a medium red heat. These heated tools are then transferred to the lower chamber where they attain the heat of this chamber or about 2200 degrees F. The work is then withdrawn and cooled until warm enough to just permit handling, either by quenching in oil or by revolving in an air blast. The work is next plunged into a bath of tallow having a temperature of 200 degrees F., which is next raised to about 520 degrees F., after which the tools are withdrawn and plunged into cold oil.

Another method which is considered very satisfactory and which results in very little scaling of the work requires first a thorough cleaning of the steel from oil or grease and the removal of all scale. The tool while cold is then immersed in water and rolled in powdered boracic acid, after which it is preheated slowly to about 1200 degrees F., and then again rolled in powdered boric acid. In this way, the tool is covered with a coating of boric acid, in order to protect it from decarburization. The next step is to replace the work in a furnace and heat it quickly to about 2300 degrees F., and then quench in an oil bath. For tempering, a temperature of 900 degrees F. and cooling in the open air is recommended. The coating of boric acid may be removed by immersing the tool, when perfectly cold, in fresh cold water. This method of heat-treatment is particularly recommended for twist drills, taps, dies, milling cutters, and similar tools.

High-speed Steel Cutting Ends on Tools. — High-speed steel is much more expensive than plain carbon steel, principally because of the elements, such as tungsten, etc., which are used to give the former its unusual property of retaining, at relatively high temperatures, sufficient hardness for cutting metals. In order to reduce the cost of certain classes of metal-cutting tools, such as are used for turning, planing, milling, etc., many manufacturers use tools having an ordinary steel shank and a high-speed steel cutting end. This cutting end or "bit" may be a

separate piece which is inserted in a tool-holder or it may be welded to the tool shank. The welded tool is practically the same as a solid high-speed steel tool, and as the cutting end and shank are united, the heat generated by cutting is conducted from the cutting point the same as though the tool were made entirely of high-speed steel. When the welding is done electrically, a flat piece of high-speed steel may be spot-welded to a seat formed at the end of the shank, or an entire cutting end of high-speed steel may be butt-welded to the shank or body made of low-grade carbon steel. After the welding operation, the tool should immediately be placed in a furnace for heat-treatment, because stresses are set up that will cause the high-speed steel to check or crack if a decided drop in temperature occurs after welding. The welded tool should remain in the furnace for several hours and be cooled very slowly in order to secure thorough annealing. After annealing, the tools may be reheated, forged, and tempered, the same as those made of solid stock.

Another method of welding high-speed steel to low-carbon steel is by the Rosner process. The welding is done in a gas furnace at a temperature above 2000 degrees F., and a special flux is used. The hardening of the tool is done at the same time that the weld is made, and without the use of an air blast.

Uses of High-speed Steel. — The commercial importance and value of high-speed steel in the machine building field are based primarily upon its fast cutting qualities in the removal of metal. It is not economical to attempt to make forgings too close to the finished size, and tools capable of high cutting speeds and heavy deep cuts greatly reduce the machining cost and increase production. While castings can be molded close to a given form or size without difficulty, it is often necessary to provide excess metal which must afterwards be removed in order to secure clean solid bearing surfaces free from sandy spongy spots or other defects, and high-speed steel is of great value for all work of this kind. In some cases, castings are made over-size to allow for warping, and considerable excess metal must be removed for this reason. The modern high-speed steel drills make it possible to drill many holes from the solid cheaper than they could be

finished by first coring and then using rose or other reaming tools. The great increases in drilling speeds as the result of high-speed steel drills have been the means of a wonderful advancement in drilling practice generally, although it was necessary for the drilling machine manufacturer to supply a machine sufficiently rigid and powerful to enable the high-speed steel drill to operate efficiently. Tools made of high-speed steel are not only invaluable for heavy cutting, but also for taking light cuts at increased speeds. This kind of steel is also extensively used for other tools designed to operate in holes, such as multiple-lipped drills and reamers of the rose and finishing types. Milling cutters, gear-cutters, forming tools, and cutting-off saws represent other very important applications of this modern steel to cutting tools. Most milling cutters larger than about 4 inches have inserted blades attached in some way to a body made of cheaper material, and the inserted blade construction is also common to the large cutting-off saws.

Many tools which operate with a shearing cut, such as the blades of sheet-metal shears, punches, and blanking dies are now made of high-speed steel. Blanking dies are ordinarily formed of one solid piece of steel, if small, whereas larger sizes have only a high-speed steel face in order to reduce the cost. Difficulty which has been experienced with high-speed steel when it has been used for such tools as punches, taps, or small drills has frequently been due to the fact that the steel has not been properly tempered so as to secure the right combination of hardness and toughness. Many of the dies used for drawing wire and for cold-drawing rods or shafting are made of high-speed steel because of its superior wearing qualities. (Dies for very small wire are made of diamonds, and chilled cast iron is used instead of high-speed steel for some cold-drawing operations.) High-speed steel has not only proved invaluable in machine shops, but is used considerably outside of the metal-working field, as, for example, in the making of cutters for wood-working machines, knives for paper-cutting machines, and for a variety of other purposes.

CHAPTER XIII

CAST IRON

CAST iron has been defined by the International Association for Testing Materials as iron containing so much carbon that it is not malleable at any temperature. Iron containing more than 2.2 per cent of carbon would conform to this definition, but the carbon content of ordinary commercial cast iron usually varies from 3 to 4 per cent. The pig iron obta ned by smelting iron ore in the blast furnace might properly be called cast iron, but the latter term is commonly applied to the more refined product obtained by remelting pig iron (combined with a certain percentage of scrap metal) in either a cupola or air furnace preparatory to pouring it into suitable molds. There are three grades of cast iron known as "gray cast iron," "white cast iron," and "mottled cast iron." The quality of the cast iron, or the grade to which it belongs, depends largely upon the carbon content and the form of the carbon, or the extent to which it is chemically combined with the iron. Much of the carbon in gray cast iron is in the form of graphite. The thin flakes of graphitic carbon are mechanically mixed with the mass of iron, which accounts for the gray appearance of a fracture. Most of the carbon in white cast iron is chemically combined with the iron instead of being in the graphitic state, although it contains a small amount of graphite. The mottled cast iron is a cross between gray and white cast iron or is an intermediate grade, part of the carbon being chemically combined with the iron and the rest in a free or graphitic state. The gray cast iron is much softer than the other grades and less brittle, and the white cast iron is the hardest and most brittle. The strongest grade is one that is intermediate between the extremes of the gray and white qualities. The hardness of cast iron varies

greatly, as the gray quality may be very soft and the white cast iron extremely hard and brittle.

Production of Iron Castings. — The formation of iron castings requires, in the first place, the melting of pig iron and scrap material proportioned to produce the desired quality of cast iron, and, in the second place, the preparation of one or more molds which conform to whatever size and shape of casting is to be made. That part of the work which includes melting and pouring the iron is known as "founding" or foundry practice, whereas the preparation of the mold includes patternmaking and molding. The pattern is usually made of wood, although metal patterns are common, especially for making comparatively small castings. The shape of the pattern conforms to whatever exterior shape is required for the casting, and interior openings or passageways are obtained by means of cores set into the cavity formed in the mold by the pattern. The mold is made of sand which may be left in a "green" or moist state, or the sand mold may be baked to harden it and make it more durable.

The pig iron and scrap material are usually melted in a furnace known as a "cupola" in which iron and fuel are charged together, although the reverberatory or air furnace is sometimes used. This type of furnace is so arranged that the iron and fuel are placed in separate compartments. When a cupola is to be fired or prepared for melting a charge of iron, the bottom is first covered with a layer of sand 5 or 6 inches thick and then the fuel is inserted. Coke is generally used, but anthracite coal is burned in some cupolas. In addition to this bottom bed of coke, there are layers of coke between the layers of pig iron and scrap which are to be melted. One of the important points about charging a cupola is to determine how much fuel there should be in the bottom bed and also the amount to use between the layers of iron. The amount of iron in the different charges is another important point, there being, as a rule, from $2\frac{1}{2}$ pounds up to 4 pounds of iron for each pound of coke in the bed for the first charge of iron. The succeeding charges or layers of iron are somewhat smaller. The pig iron is

generally thrown into the cupola first and then the scrap material, because the latter melts more readily than pig iron; the result is that the pig iron and scrap melt at about the same time, because the pig iron reaches the melting zone first.

Some flux, such as limestone, also forms part of the cupola charge. This flux serves two purposes, as it forms a slag by combining with the silica from the charge and also provides a protective covering for the bath of molten metal. After the cupola has been charged as described, it is generally allowed to stand for about half an hour before opening the air blast. When this practice is followed, the lower part of the charge heats up considerably, and melting begins rapidly and continues at a uniform rate when the blast is applied. The charge of iron in the cupola should be somewhat greater than is required for filling the molds, because the iron which comes out of the cupola last contains more or less slag which would cause defective castings. This part of the charge is commonly used for making rough castings that do not require finished surfaces. Castings are sometimes made from molten metal obtained directly from the blast furnace.

Mixtures for Different Grades of Cast Iron. — The grade or quality of cast iron depends not only upon the proportion of pig iron and scrap iron, but also upon the grades of these materials, as well as the flux and fuel used. There are many different grades and brands of pig iron, and the scrap iron also varies greatly and may consist of cast iron or steel chips from machine shops, the gates or sprues of castings, defective castings, wrought iron scrap, steel scrap, or malleable scrap. A cupola charge contains ordinarily about 60 per cent of pig iron and 40 per cent of scrap when the castings are intended for general work, although for some special purposes pig iron alone may be used. The use of scrap reduces the cost of the charge, but increases the melting loss. The addition of steel scrap strengthens the castings, about 25 per cent being used for obtaining very strong castings.

When determining a cupola mixture, the changes that occur while melting must be considered. For instance, silicon is

reduced from 0.20 to 0.25 per cent, whereas there is a slight increase in the sulphur content. If the limit for silicon is 2.15 per cent in the castings, a silicon content of 2.40 per cent in the charge would be needed to offset the 0.25 per cent loss in melting. The amount of silicon, manganese, and graphitic carbon is decreased by remelting iron in a cupola and the combined carbon is increased. If soft gray iron is remelted a few times, it gradually becomes harder and finally a very hard white iron is produced.

Composition of Cast Iron. — Commercial cast iron varies considerably in its composition which depends upon its intended use. A cast iron recommended by the Society of Automotive Engineers for automobile construction, but one that is applicable to many other classes of work, has the following composition: Total carbon, from 3.25 to 3.50 per cent; manganese, preferably 0.50 per cent, and ranging from 0.40 to 0.70 per cent; silicon, preferably 2 per cent, and ranging from 1.90 to 2.20 per cent; phosphorus, from 0.6 to 1 per cent; sulphur, not over 0.1 per cent. Cast iron of this composition is strong and fairly close-grained, and it conforms closely to the cast iron used by many machine tool manufacturers.

A committee of the American Society for Testing Materials recommended a maximum sulphur content in "light" gray iron castings of 0.08 per cent; in "medium" castings, 0.10 per cent; in "heavy" castings, 0.12 per cent. These percentages are the maximum allowable in each case. The term "light casting" is applied when there is no section over ¼ inch thick, and "heavy casting" is used when there is no section less than 2 inches thick. The silicon content should preferably be varied in accordance with the thickness of the castings. The composition recommended for heavy machinery castings is as follows: Silicon, from 1 to 1.5 per cent; sulphur, less than 0.10 per cent; phosphorus, from 0.30 to 0.50 per cent; manganese, from 0.80 to 1 per cent; total carbon, low. For medium castings: Silicon, from 1.5 to 2 per cent; sulphur, less than 0.09 per cent; phosphorus, from 0.40 to 0.60 per cent; manganese, from 0.60 to 0.80 per cent. For light castings: Silicon, from 2 to 2.5 per

cent; sulphur, less than 0.08 per cent; phosphorus, from 0.5 to
0.7 per cent; manganese, from 0.5 to 0.7 per cent.

Influence of Carbon on Cast Iron. — The characteristics of
cast iron depend chiefly upon the amount and condition of the
carbon content. The influence of carbon, however, is modified
to some extent by other elements which will be referred to later.
The graphite in gray cast iron, which is practically pure carbon,
does not exert any direct influence upon the molecules of the iron,
as it is a mechanical mixture and not chemically combined with
the iron. Graphite does, however, affect the tensile strength,
because the flakes of graphite separate the grains of metal and
reduce the cohesion. While cast iron that has considerable
graphite is soft and can be machined readily, it has a relatively
low tensile strength. The principal factor affecting the hardness,
soundness, tenacity, and freedom from internal stresses in cast-
ings is the amount of carbon in chemical combination. The
amount of combined carbon varies from 0.05 per cent in the
softest cast iron to about 0.60 per cent in the strongest cast iron.
The amount of silicon and sulphur regulates the separation of
carbon in the graphitic form so that the sulphur content in-
dicates the relation between the free and combined carbon.

Influence of Silicon on Cast Iron. — Silicon has a very decided
effect upon the characteristics of cast iron. The addition of
silicon makes the iron softer, because it tends to separate the
carbon as graphite and the hardening effect of the silicon re-
quired to do this is less than that of the combined carbon con-
verted into free or graphitic carbon. By varying the silicon
content, the quality of the cast iron can be changed according
to its intended use, although the effect of other elements must
not be ignored. A silicon content of 1.8 per cent gives the
maximum tensile strength and a silicon content of 0.9 per cent
gives the maximum crushing strength. The greatest general
strength, including crushing, tensile, and transverse is obtained
with a silicon content of 1.4 per cent.

Influence of Sulphur, Manganese, and Phosphorus. — The
addition of sulphur increases the hardness and brittleness of
cast iron, its effect being opposite to that of silicon. Sulphur

also tends to cause defective castings as it makes the iron more sluggish when pouring it into the mold. Sulphur also increases the shrinkage and resulting internal stresses. For these reasons it is essential to keep the sulphur content low, particularly if the castings are small.

The effect of manganese is also opposite to that of silicon as it retards the separation of graphite by combining with the carbon, thus making the iron harder and stronger. Manganese also combines with sulphur and is removed with the slag.

Phosphorus increases the hardness and brittleness of castings and reduces the tensile strength, but it lowers the melting point and increases the fluidity of the molten iron.

Other Alloying Elements for Cast Iron. — Chromium, nickel, titanium, and vanadium have been introduced into cast iron, although they are less common than the other elements previously referred to. Chromium strengthens cast iron, but makes it hard and brittle. The use of 1 or 2 per cent of nickel strengthens cast iron and improves its chilling power, but it is not used to any great extent on account of the cost. Heavy chilled castings such as car wheels and rolling mill rolls sometimes contain nickel or chromium. It is doubtful if titanium is beneficial in cast iron, for while it tends to remove the sulphur, this is offset by the removal of oxygen which is highly beneficial. In fact, titanium is one of the best deoxidizers known in metallurgy. The influence of vanadium is to increase the resistance of the cast iron to wear.

Strength of Cast Iron. — The ultimate tensile strength of cast iron may generally be assumed to be 15,000 pounds per square inch; the ultimate shearing strength, 18,000 pounds per square inch; the ultimate compressive strength, 80,000 pounds per square inch; and the modulus of elasticity, 12,000,000. Castings are usually under considerable internal strain as the result of unequal contraction, although this strain may gradually disappear. The working stresses for ordinary castings should be limited to from 2000 to 4000 pounds per square inch, depending upon the service. If loads are to be applied suddenly, the tensile strength should be limited to 2000 pounds per square

inch and if the direction of the load reverses, the limit should be 1000 pounds per square inch. It may be necessary to further limit these unit loads to suit the ratio of the length to the section, as required for columns or other parts in alternate extension and compression. The strength of cast iron begins to decrease when the temperature rises above approximately 500 degrees F.; at 900 degrees F., it has 75 per cent of the original strength; and at 1100 degrees F., 40 per cent of the original strength. The melting point of cast iron is about 2300 degrees F., and its specific gravity, about 7.2, the weight per cubic inch being 0.26 pound.

Growth of Castings or Change in Size. — Cast-iron parts which are subjected to repeated heating and cooling gradually increase in size or "grow," which is a quality peculiar to cast iron. This growth is so pronounced that annealing ovens 8 feet in length have been known to grow to 9 feet in length as the result of being heated red hot for prolonged periods between which they are permitted to cool. Furnace grates and similar parts are affected in the same way. Experiments have shown that the maximum growth of commercial cast iron occurs when it is heated to a temperature of 1650 degrees F. during four-hour periods, between which the casting is cooled. Cast iron subjected to this treatment increased in size from 35 to $37\frac{1}{2}$ per cent, and the weight increased from 7.8 to 8.6 per cent. This increase of weight indicates that gases were absorbed from the air, there being an oxidation of silicon and of carbon. The effect of gases on the growth of cast iron was shown by the fact that a test piece increased in size and weight decidedly when heated in a muffle furnace, but contracted slightly when heated in a vacuum. White cast iron is preferable to the gray cast iron where difficulty is experienced on account of growth. It should contain about 3 per cent of carbon and the silicon content should not exceed from 0.2 to 0.3 per cent.

Methods of Hardening Castings. — Either rough castings or those which have been machined can be hardened throughout by subjecting them to the following heat-treatment: After heating the casting to a cherry-red, it is quenched in a bath,

preferably of sulphuric acid (having a specific gravity of from 1.8 to 1.85) to which is added a suitable quantity of arsenic. Three-fourths pound of red arsenic crystals to one gallon of sulphuric acid having a specific gravity of about 1.84 is preferable. To obtain the best results, the red arsenic crystals should be added to the sulphuric acid and the bath should not be used for about a week, to insure thorough saturation. This bath has a high heat-conducting power which is essential, and the more rapidly the cast iron is cooled, the harder it is made. The bath should be contained in a lead jar or tank surrounded by a water jacket. If only one section of a casting requires hardening, this may be done by simply immersing that part.

Seasoning Cast Iron. — Cast iron, like steel, is subject to more or less change of shape, particularly after the hard outer skin or surface has been removed by turning or planing. One method of avoiding these changes in the finished part is to allow the castings to "season" or stand for several weeks or even months after taking the roughing cuts and before finishing them. These changes are caused by the internal stresses in the casting, which are gradually readjusted and neutralized by seasoning.

In order to avoid a long seasoning period, castings that must retain their shape as much as possible are often subjected to some kind of heat-treatment. A method which has proved successful, as applied to the cast-iron beds of measuring machines, is in the nature of an annealing process. After rough-machining, castings are placed in a furnace and heated to a low red heat. Another method of annealing is by dipping the casting repeatedly in hot water. The release of the internal stresses will also be accelerated if the casting is subjected to repeated shocks or vibration, while cold. In making surface plates and straight-edges, good results have been obtained by first rough-planing the work and then subjecting it to a temperature varying between 350 and 550 degrees F., the temperature depending upon the size and shape of the casting. After this heat-treatment, the castings are finish-machined and then scraped. Even though a casting is well-seasoned, the shape may change if it is subjected to unusual degrees of heat and cold, but unless these changes are

sufficient to cause warping, the casting will return to its original
shape.   Castings that have been left in the yard and exposed to
the weather for a long period will be seasoned the same as those
which have been heat-treated.

Chilled Castings. — The hardness of cast iron depends en-
tirely upon the condition of the carbon it contains.   If the iron
is cooled so rapidly that the crystals or flakes of graphite will
not have time to separate, the carbon will remain in the combined
form and a very hard iron will be produced.   In the production
of chilled castings, this rapid cooling is effected either by metallic
molds or by inserting pieces of iron or "chills" into the mold.
When the molten metal comes into contact with these metallic
surfaces, it is cooled rapidly and thus hardened.   The more
rapid the rate of cooling, the whiter will be the iron and the
greater the depth of the chilled or hardened part.   These hard
outer surfaces on chilled castings are desirable for many purposes,
especially where the surface of the casting is subjected to con-
siderable abrasion or wear.   Steel castings are used for the jaws
of crushing machines, stamps, certain classes of rolls, and for
many other purposes.   The wearing surfaces of machine tool
beds are often chilled to produce a better wearing surface by in-
creasing the density and hardness of the metal.

The depth of the chilled part of a casting may vary from $\frac{1}{8}$
to 1 inch or more, and it is partly dependent upon the thickness
of the chill or the metallic part of the mold, and to some extent
upon the temperature of the metal when poured.   While the outer
surface of a chilled casting is extremely hard, the inner surface
is comparatively soft and tough.   The chilling process, or the use
of chills in molds, is not only employed to secure hard castings,
but also to obtain a more uniform cooling of the metal; in fact,
chills are sometimes used primarily to control the rate of cooling.
When a casting has a heavy section adjoining a relatively light
section, the latter naturally tends to cool more rapidly, which
may result in a defective casting, on account of the metal being
drawn away from the thick section at the point where it joins the
thinner part.   This may be avoided and the formation of in-
ternal cavities prevented by using chills which will cause the

heavy section to cool more rapidly. If the section that is chilled in this way must be machined afterwards, care must be taken to use chills that are just thick enough to increase the rate of cooling the required amount. If the chills are too thick, the casting will be hardened excessively and machining will be either difficult or impossible.

The car wheel is one of the most common as well as important examples of chilled castings. The tread or periphery of such wheels is chilled so that they will resist wear, due to rolling on the rails and the abrasive action of the brakes. The chilled section usually extends to a depth of from ⅜ to ¾ inch. This hard outer surface gradually changes into the ordinary gray cast iron of which the remainder of the wheel is composed. The iron used for making car wheels is selected by chemical analysis. The controlling element in the formation of the chilled surface is silicon. If the silicon content is higher than 0.80 or 0.90 per cent, the chilling effect will not be obtained, and for this reason iron of low silicon content must be used. The use of the right grade of coke for melting the iron is also very essential, what is known as the "72-hour coke" being commonly used. The chill in the mold is in the form of a ring which surrounds the wheel tread. This chill may be a plain smooth ring, or it may be arranged to contract as the mold cools. When a plain ring is used, it naturally expands when heated and moves away from the shrinking metal of the wheel. To avoid this, the "contracting chill" has been used. A simple form consists of a ring having a large number of radial slots extending through the inner half. When the molten metal comes into contact with the inner ends of the radial sections formed by the slots, these are heated, but the outer ring remains comparatively cold, so that the expansion of the radial sections actually reduces the inside diameter and the chill contracts with the wheel. The outer ring may be hollow and have a stream of water circulating through it to keep it cool. Car wheels are annealed after casting by placing them in a pit while still red, where they are allowed to remain while they cool slowly.

Malleable Iron Castings. — Ordinary castings are quite brittle and are often broken by a shock or blow. In order to secure a tougher material, ordinary white-iron castings are subjected to a heat-treating or annealing process which makes them partly malleable and much tougher than unannealed castings. The castings that are to be made malleable are produced in the ordinary manner except that an air furnace is generally used.

The softest and most ductile constituent in any iron product is ferrite, which is observed in carbonless iron when a polished and etched specimen is examined under the microscope. As a good grade of wrought iron is very low in carbon, it consists principally of ferrite, although there are minute particles of slag which cannot be entirely removed in the process of manufacture. The object of annealing white-iron castings is to separate the hard carbide of iron into iron and carbon; consequently the outer part of the casting is changed to ferrite and the interior is made up of ferrite contaminated with free carbon. The structural composition of wrought iron and malleable iron is similar, with the exception of the slag in wrought iron and the free carbon in malleable iron.

While malleable cast iron is not as strong as steel and is not suitable when a high tensile strength is required, it will withstand shocks better than ordinary steel and can be bent or twisted. One of the great advantages of malleable iron is that it is not subject to crystallization or "fatigue" and it is capable of resisting repeated shocks for long periods. In fact, it is claimed that a good grade of malleable iron will stand as severe a test after twenty-five years of use as when originally made. Malleable iron also resists corrosion much better than either steel or wrought iron. The tensile strength of malleable castings ordinarily varies from 35,000 to 55,000 pounds per square inch, with from 3 to 8 per cent elongation in two inches.

When making castings that are to be converted into the malleable product, it is essential to use the proper grade of pig iron, to pour the metal rapidly, to secure sufficient oxidation of the silicon and carbon, and finally to anneal the castings properly. An air furnace is generally used for melting the charge

for castings that are afterwards to be made malleable. The open-hearth furnace has also been used to some extent. While a cupola may be used, the metal is liable to burn and more difficulty is experienced with defective castings; consequently, the use of the cupola for this branch of foundry work is practically obsolete. A higher annealing temperature is also required than is necessary when the air or open-hearth furnace is used. The melting cost, however, is lower when using a cupola.

Prior to annealing the castings, they are cleaned either by tumbling, pickling, or by means of a sand-blast. They are then placed in malleable-iron annealing boxes or pots and the spaces between the castings are filled with crushed slag, rolling mill scale, or a mixture of both. Hematite ore is also used, especially if a cupola was used when making the castings. The minimum temperature in the annealing furnace should be 1350 degrees F. and the maximum, 1450 degrees F. The furnace is quickly heated to the desired temperature, which is maintained for about sixty hours. The furnace is then cooled slowly until the pots are black, and then the contents are removed. Natural gas is considered the best fuel for annealing furnaces, although producer gas is satisfactory. Some castings are annealed without packing them in annealing pots as described. In this case, a muffle oven is used. The castings are packed in the oven with the scale or other material. This method is applied when the castings are long or of such a shape that pots cannot readily be used.

The composition of a malleable iron recommended by the Society of Automotive Engineers is as follows: Manganese, preferably 0.50 per cent, but varying from 0.30 to 0.70 per cent; silicon, 1 per cent maximum and 0.60 per cent desired; phosphorus, 0.20 per cent maximum and 0.17 per cent desired; sulphur, 0.06 per cent maximum. A malleable casting which varies decidedly from the composition given is liable to be brittle, and in any case proper annealing is necessary. Malleable castings are extensively used in the manufacture of agricultural machinery, and also in railway equipment and for many other classes of work subjected to shocks and corrosion.

CHAPTER XIV

STEEL CASTINGS

STEEL castings are formed by pouring molten steel into suitable molds, the general procedure in this respect being practically the same as in the iron foundry. The shape of a steel casting, like one made of cast iron, depends entirely upon the shape of the mold, and it is not rolled or forged. The steel used for making steel castings may be produced either by the Bessemer, open-hearth, electric, or crucible processes. The steel cannot be melted in a cupola, because the impurities will be absorbed from the fuel, and it is also difficult to obtain the high temperature necessary. The terms "cast steel" and "steel casting" are sometimes used interchangeably. Tool or crucible steel was formerly known as cast steel, but this usage of the term "cast steel" is now almost obsolete and should be discontinued, because it results in confusion as to the intended meaning.

Steel castings are especially useful for machine parts that must withstand thrust or shocks or those subjected to heavy loads. Great improvements have been made in the production of steel castings, especially in regard to the tensile strength, elastic limit, and resistance to impact. Steel castings are stronger than either wrought iron, cast iron, or malleable iron, and they are very tough. Steel castings are used for such parts as cylinder covers, cross-heads, cross-head guides, valve chest covers, bearing caps, bed-plates and housings, sternposts for ships, rudder frames, gun mounts, locomotive side frames, etc. Steel castings are of special importance in ship construction and for various classes of railway equipment, although they are applied in a great variety of industries.

Strength of Steel Castings. — The tensile strength of steel castings has been increased about 50 per cent during a period of twenty-five years, and the resistance to impact has been increased

to a still greater extent. The tensile strength of steel castings produced in modern steel foundries ordinarily varies from 60,000 to 80,000 or 85,000 pounds per square inch. The specifications prescribed by the American Society for Testing Materials include two general classes of steel castings known respectively as Class A and Class B. The former represents ordinary castings for which no physical requirements are specified. The Class B castings for which physical requirements are specified are divided into three grades, designated as hard, medium, and soft. The minimum requirements as to tensile properties for Class B castings are as follows: Soft grade, tensile strength, 60,000 pounds per square inch; yield-point, 27,000 pounds per square inch; elongation in two inches, 22 per cent; reduction of area, 30 per cent. For the medium grade, tensile strength, 70,000 pounds per square inch; yield-point, 31,500 pounds per square inch; elongation in two inches, 18 per cent; reduction of area, 25 per cent. For the hard grade, tensile strength, 80,000 pounds per square inch; yield-point, 36,000 pounds per square inch; elongation in two inches, 15 per cent; reduction of area, 20 per cent.

The specifications of the Ordnance Department require minimum tensile strengths varying from 60,000 to 85,000 pounds per square inch for different grades of castings, with yield-points varying from 28,000 to 53,000 pounds per square inch; reduction of area, from 20 to 30 per cent; and elongation in two inches, from 17 to 22 per cent. Test-bars ½ by 1 inch must withstand being bent cold through an angle of 120 degrees around a 1-inch pin. As steel castings are much stronger and tougher than cast-iron castings, they can be made thinner and lighter, which is an important feature for many classes of service.

Materials for Making Steel Castings. — The raw materials from which steel castings are made are steel scrap, pig iron, and iron ore, the materials and their proportions varying according to the process and the type of furnace used. The scrap is made up of the cropped ends of plates, forgings, and structural material, and the borings and turnings from machine shops. The amount

of ore required depends upon the nature of the other ingredients. In some cases, where scrap could not be procured, the charge has consisted entirely of pig iron and ore. The ore is used chiefly for its oxidizing effect on the metalloids, carbon, silicon, sulphur, and phosphorus. Hematite ore is the kind generally used, and the iron it contains is a secondary consideration.

Processes for Making Steel Castings. — The method of making steel castings varies according to the process of melting the raw materials or of producing the steel, and in regard to certain other details which will be referred to. The steel for comparatively small castings may be made by the Bessemer or crucible processes, whereas for large castings the open-hearth furnace is preferable. The electric furnace is now used extensively in connection with this work, as explained later. The crucible process is sometimes used for making very thin castings, as the metal may be poured directly from the crucible which is kept in the furnace until needed. Ladles may also be used, especially for the larger castings. The crucible process is adapted to castings made of ordinary carbon steel (except when the carbon content is very low) and of nickel-chromium, tungsten, or molybdenum steels. Manganese steel can be produced more profitably by the Bessemer process.

In most American steel foundries using Bessemer converters, the side-blown type is employed. These converters all have an acid lining because of the melting losses incident to the Bessemer process. The basic converter is used in some parts of Europe. The air or blast of these side-blown converters passes through a trunnion and then through tuyeres at the side. When an ordinary converter is used, a cupola is required for melting the charge and a smaller cupola for melting the recarburizers and alloys. When a converter is to be blown, it is preheated either by placing a fire in it or by means of an oil burner. This preheating continues for three or four hours, and when it is blown to a yellow heat, it is tipped forward and charged with molten metal from the cupola. The blast, which has a pressure of about four pounds per square inch, is then turned on. After the charge has boiled four or five minutes at intervals of from

3 to 10 minutes, the "final flame" appears, and then the blast is shut off and the charge is re-carburized and is ready for pouring.

In order to avoid using a cupola for melting the charge, which makes it necessary to convey the molten metal from the cupola to the converter, what is known as a *stock converter* is sometimes used. The pig iron and scrap are charged into this converter, and when this charge is melted, the metal is blown in the usual manner. Oil burners are used for melting the charge; however, unless oil is very cheap and coke is expensive, this method is not profitable.

The open-hearth process is considered economical when castings are to be made that average over 50 pounds in weight. The open-hearth furnaces used in American steel foundries are usually of from 15 to 20 tons capacity, although they vary from 8 to about 35 tons capacity. Open-hearth steel would be suitable for making small castings were it not for the difficulties due to a rather low initial temperature and the chilling of the metal when an attempt is made to pour a large number of small castings. The disadvantages of the process are that only one kind of steel can be made in one heat; the furnace must be worked continuously; and the initial cost of the installation is relatively high.

When the acid process is employed, the charge contains from 20 to 35 per cent of pig iron, the remainder being scrap. The scrap is low in carbon and considerable pig iron is necessary to make the steel boil. More pig iron is used in making basic steel, the proportion being about half pig iron and half scrap. Some open-hearth furnaces are of the rolling or tilting type so that, when the metal is ready to pour, the melting chamber is tilted by means of electric or hydraulic machinery until the metal flows from the spout into the ladle. Another type of furnace is so arranged that it can be lifted from its setting for pouring the metal directly into the molds, a crane being used to convey the furnace from one mold to another.

The molds for making steel castings must be made of some material that will withstand considerable heat, as the pouring temperature for steel varies between 2500 and 2700 degrees F.

Because of this high temperature, molding sand must contain enough silica to prevent melting or softening by the heat of the steel. Sand having considerable silica is often mixed with just enough fireclay to give the necessary plasticity.

Electric Furnace in the Steel Foundry. — The electric furnace has proved valuable for making steel castings as well as for producing special alloy and tool steels, and many of these furnaces have been installed in steel foundries. The electric furnace produces a very pure steel and the high temperatures obtainable make it possible to cast very light sections. In fact, the temperature may be varied according to requirements, lower temperatures being maintained when pouring relatively large castings. The use of the electric furnace tends to eliminate blow-holes or pipes in castings, and any alloying elements that may be required can be added in the furnace. Electric furnaces of the larger sizes are sometimes used in conjunction with open-hearth furnaces and Bessemer converters. The partially refined molten charge may be obtained either from an open-hearth furnace or a Bessemer converter, as in the duplex or "hot metal" process, or the converter, open-hearth furnace, and electric furnace may be used in combination as in the triplex process, which is described more in detail in Chapter IX. The basic electric furnace is generally used in steel foundries as well as in other branches of the steel industry. The basic slag which may be used with the basic electric furnace reacts chemically with the impurities in the molten charge and removes them the same as with the basic open-hearth furnace. Thus phosphorus may be removed by the use of oxides in the slag and also sulphur and oxygen, since the electric furnace can operate under reducing or oxidizing conditions. If the specifications as to the sulphur and phosphorus contents in the castings are not exacting and a good quality of scrap is available, an acid-lined furnace may be used. The general practice when the charge is melted in the furnace is to melt rapidly and then allow the molten steel to remain in the furnace long enough for deoxidizing, after which it is poured.

Annealing Steel Castings. — Steel castings are ordinarily annealed by heating them in a furnace to a temperature which is

usually between 1500 and 1600 degrees F. This heat-treatment, if properly conducted, improves the granular structure of the metal, increases its ductility and tensile strength, and also relieves internal stresses in the castings. The annealing furnace may be heated by coal, oil, natural gas, or producer gas. It is essential to secure even or uniform heating of the castings, and all the castings in a charge should be of practically the same size. If some castings are large and others quite small, the latter will be injured by oxidation in scaling and the large sizes
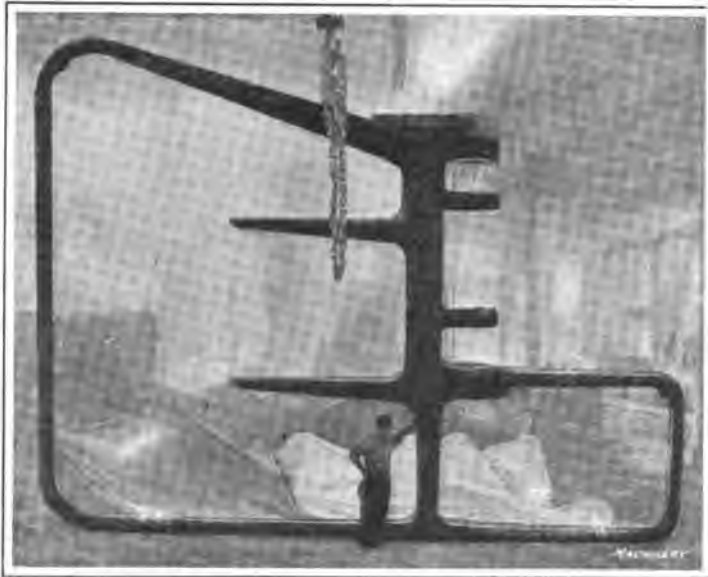
Fig. 1. Cast-steel Rudder Frame which weighs about 20 Tons·

may not be sufficiently annealed. The annealing practice recommended by the American Society for Testing Materials is as follows:

1. The castings should preferably be sufficiently cleaned of adhering sand before annealing, to insure thorough and uniform heating.

2. The castings should be heated slowly and uniformly to temperatures varying with the carbon content of the steel, and approximately as follows: Carbon, up to 0.16 per cent, 925

degrees C. (1697 degrees F.); from 0.16 to 0.34 per cent of carbon, 875 degrees C. (1609 degrees F.); from 0.35 to 0.54 per cent of carbon, 850 degrees C. (1562 degrees F.); from 0.55 to 0.79 per cent of carbon, 830 degrees C. (1526 degrees F.).

Nothing in these recommendations shall be understood as preventing the temperatures being 50 and, in special cases, 100 degrees C. higher than those given in the table, when necessary to attain the desired result.

3. The castings should be kept at the maximum temperature a sufficient length of time to insure the refining of the grain. In
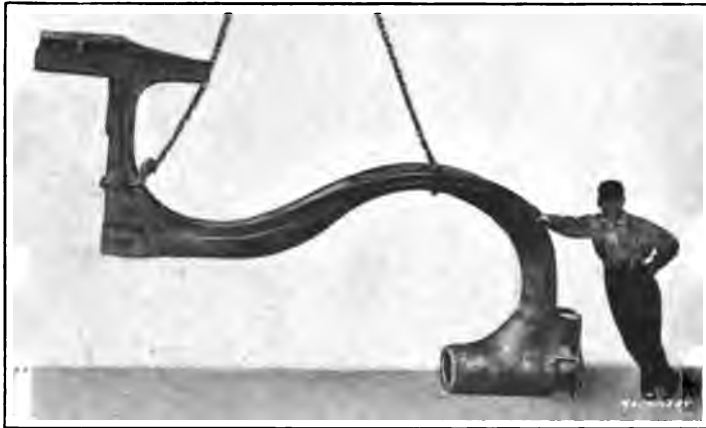
Fig. 2.   Cast-steel Sternpost for Torpedo Boat Destroyer

general, the heavier the sections of the casting, the longer must be the time of exposure to the maximum temperature.

4. The castings should be cooled slowly and uniformly in the furnace, when it is desired that the steel shall possess the maximum softness.

The castings may be cooled at an accelerated rate, when it is desired that the steel possess rather higher tensile strength and elastic limit than can be procured by very slow cooling. This cooling must be so conducted as to leave the steel reasonably free from cooling stresses. The manner of carrying out this accelerated cooling should be such as will attain the desired result. For instance, the castings may be withdrawn from the furnace and buried in a bed of material that is a poor conductor of heat;

or the annealing furnace may be so thrown open that it will cool more rapidly than it left closed. Should the castings be of such uneven section that they cool at unequal rates at various points when the furnace is opened, especially if the carbon of the steel is high, the furnace should be closed after the castings have become black, and their further cooling so retarded that the stresses set up by the unequal rates of cooling are relieved.

Large Steel Castings. — The work of the steel foundry ranges from small castings weighing a few pounds up to massive steel parts weighing many tons. The examples shown in the accompanying illustrations indicate, in a general way, what has been accomplished in producing very large castings. The cast-steel rudder frame shown in Fig. 1 is about 22 feet high, 28 feet long over all, and weighs approximately 20 tons. As the section is relatively small for a casting of this size, it represents a rather difficult example of steel foundry work. The total shrinkage in the height and length of a casting of this kind would be from 2 to 3 inches; consequently, the mold must be rammed loosely enough so

Fig. 3. Steel Casting for the Bow of a Ship

that the metal will crush it when cooling. If this did not occur, the metal would either crack or stretch and become weakened. As soon as the metal solidifies, the cope should be removed, thus uncovering the casting and assisting in the shrinkage.

Fig. 2 shows the sternpost of a torpedo boat destroyer, the size of the casting being indicated by the man standing beside it. The large casting illustrated in Fig. 3 is located at the extreme end of the bow of a naval vessel. The edge at A is quite sharp for cleaving the water and reducing resistance. The steel

generally used for locomotive side frames is an ordinary carbon steel containing about 0.30 per cent of carbon, but vanadium steel is also employed.   The frame illustrated in Fig. 4 contains about 0.30 per cent of carbon, and in molding it, an indentation occurred at *B* which was probably caused by gas or air being trapped in the mold in the form of a bubble.   For this reason, the casting was condemned as it was thought that there might be blow-holes in it.   In order to test the casting, it was placed under a hammer and bent to the shape shown without cracking or even checking at the bend.   An unusually large casting is shown in Fig. 5, which illustrates a rudder having a length of about 27 feet and a weight of $22\frac{1}{2}$ tons.

Composition of Steel Castings. — The composition of steel castings recommended especially for automobile construction, but suitable for many other classes of work, is as follows: Carbon, preferably 0.35 per cent with variations of from 0.30 to 0.40 per cent;

Fig. 4.   Locomotive Frame bent to Test Quality of Steel Casting

manganese, preferably 0.70 per cent and varying from 0.50 to 0.80 per cent; silicon, from 0.10 to 0.30 per cent; phosphorus, not over 0.05 per cent; sulphur, not over 0.05 per cent.   These specifications have been adopted by the Society of Automotive Engineers.   The elastic limit of an annealed casting of this composition is approximately 35,000 pounds per square inch.

The percentages of carbon, silicon, and manganese are sometimes varied according to the size of the castings or their intended use.   The following data were obtained from a German source: For small machine parts, 0.50 per cent of carbon, 0.25 per cent

of silicon, and 0.50 per cent of manganese; for large machine parts, from 0.10 to 0.40 per cent of carbon, from 0.20 to 0.40 per cent of silicon, and from 0.50 to 0.80 per cent of manganese; castings for ships, such as sternpost and rudder frames, from 0.20 to 0.40 per cent of carbon, 0.30 per cent of silicon, and 0.50 per cent of manganese. Hard castings for ore crushers, etc., from 0.80 to 1.00 per cent of carbon, from 0.20 to 0.40 per cent of silicon, and from 0.50 to 1.00 per cent of manganese.

The Union Steel Casting Co., Pittsburg, Pa., has experimented considerably with vanadium steel castings. It has been found that steel castings containing about 0.2 per cent of vanadium show a great increase in tensile strength and elastic limit. Cast-
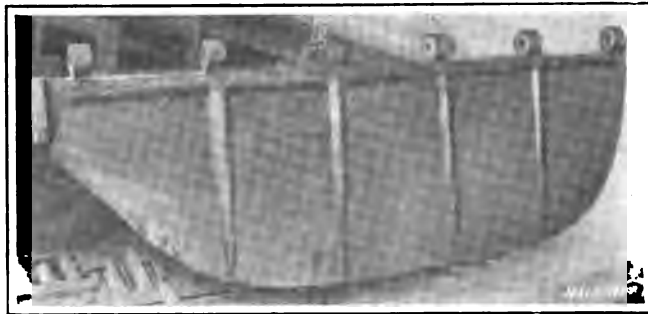
Fig. 5. Cast-steel Rudder weighing 22½ Tons

ings have been made by this company having a tensile strength of 90,000 pounds per square inch. The average tensile strength, however, is about 80,000 pounds and the elastic limit, about 45,000 pounds.

Tests have indicated that the quality of steel castings may also be greatly improved by the addition of titanium, which is said to improve the density, strength, toughness, and durability of the steel when properly applied. This improved quality is not the result of any direct or alloying effect of titanium, but as the result of its value as a deoxidizer and cleanser in removing injurious slags and occluded gases. According to one authority, vanadium is only 70 per cent as efficient as titanium. A comparative test of twenty untreated and treated steels showed an increase in the ultimate strength of approximately 15 per cent,

with no reduction in elasticity and contraction. An endurance
test made with a Wright-Souther machine showed the following
results: An untreated steel withstood 2,676,000 revolutions at
a fiber stress of 38,872 pounds, whereas titanium-treated steel
withstood 18,274,900 revolutions at pressures varying from
38,872 up to 45,939 pounds fiber stress. It is claimed that the
life of titanium-treated rails to withstand shocks and abrasion,
and the life of gears, is about 50 per cent greater than when un-
treated steel is used.

Making Manganese Steel Castings. — In making manganese
steel castings, the metal is refined in a Bessemer converter
from which it is poured into a ladle in which the proper quan-
tity of ferromanganese has been previously placed. From a
metallurgical standpoint, there is nothing to prevent the suc-
cessful production of manganese steel in open-hearth furnaces,
and it is possible that there may be some developments in the
future along this line, although at present the converter process
is strictly adhered to. The alloying material added is commer-
cial 80-per-cent ferromanganese, which is melted in crucibles in
oil-burning furnaces. The quantity of manganese required
varies somewhat with the nature of the castings, but 12.5 per
cent is a good average figure. To produce castings that will
show this amount of manganese upon analysis, it is necessary
to add about 312 pounds of 80-per-cent ferromanganese to each
net ton of steel. After the steel has been added to the alloy, the
ladle is allowed to stand for a few minutes to permit the ferro-
manganese to remove the oxygen and other gases and impuri-
ties from the metal, leaving it homogeneous and dense.

The shrinkage of the metal is unusually great, but otherwise
the principles of ordinary steel foundry practice apply in making
the patterns for manganese steel castings. The shrinkage
amounts to $\frac{5}{16}$ inch per foot. Ordinary steel shrinks only about
$\frac{3}{16}$ inch. Abrupt changes in section are more objectionable
with this steel than with other kinds. Manganese steel castings
are generally allowed to cool in the mold, and are then annealed
for from 3 to 26 hours at temperatures ranging from 1800 to 2000
degrees F. At the conclusion of this process, they are removed

red-hot from the annealing oven and are quenched suddenly in cold water. Some castings, however, need a preliminary treatment in order to remove the cooling strains, and in this case they are taken from the sand while still hot and slowly cooled in an oven, after which they are reheated for annealing and quenching, as described. Unannealed manganese steel castings are exceptionally brittle and almost glass hard. After the heat-treatment, they are tough and ductile with a tensile strength of about 90,000 pounds and an elastic limit of about 60,000 pounds per square inch. After the castings are annealed, they are cleaned and finished on grinders. Castings which must be accurately finished to given dimensions cannot be machined by ordinary methods on account of their toughness, but must be ground to size.

Semi-steel Castings. — What is commonly known as " semi-steel" and less frequently as " toughed cast iron" is produced by adding soft steel or wrought-iron scrap to the charge in a cupola. The semi-steel castings obtained from this mixture are cast in the same manner as ordinary castings. The mixture or charge for making semi-steel castings usually contains about 20 per cent of steel scrap, although any amount up to about 70 per cent may be used. Semi-steel castings have less total carbon than ordinary cast iron, there seldom being more than 3 per cent. The fine grain of semi-steel is due to the low percentage and fineness of the graphitic carbon. In producing semi-steel, it is essential to secure hot and uniform melting. A longer time is required to melt the steel, and it is necessary to have it thoroughly incorporated with the iron. It is common practice to cast the metal into pigs when first mixing the steel and iron. These pigs are then remelted, thus insuring a uniformity of texture. Semi-steel is commonly used for large gears, for the tables, saddles, slides, etc., of machine tools, and for parts requiring a good appearance.

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